Scientific Voyage
Vol. 3, No. 1,
Page 1-18 (2022)

SCIENTIFIC VOYAGE
ISSN: 2395-5546

GCECT
Publication
Jan - Mar

Cold Plasma in Research, Development and Deployment

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Abstract: Chemistry and related research, that aims to address and solve myriad challenges, is ultimately evaluated or judged from utilitarian points of view. A successful endeavor therefore not only generates a sense of satisfaction and opens up fresh research directions; it may also substantiate the novelty and apt use of the experimental methodology chosen therein. Diversity in respect of evolving research strategies, aided by simultaneous improvements and availability of associated hardware and software, progressively allow more complex challenges, which seemed beyond reach previously, to be addressed and resolved. Frequently, chemical reactions' commencements necessitate energy input in some form, and thereafter may follow either oxidative or reductive pathway. Various forms of energy employed include heat, ultrasound, light, UV, X-ray, Nuclear Radiations *etc.*, in addition to catalytic and enzymatic supports. In this context, the distinctive and novel reactive energy source of **Cold Atmospheric Plasma** (or **Cold Plasma, CP** in short) offers a simple and frequently superior alternative to a variety of studies that stipulate use of vastly expensive and very complex hardware systems. Though the history of **CP** spans over last 150 years, it remained completely dormant or sparsely researched almost till the 1980s mainly due to ignorance. At present, setting up a **CP** experimental facility or laboratory is an uncomplicated, and generally an *easy-to-finance* proposition. Convenient need based tuning and generation currently makes **CP** technology one of the user-friendliest available for contribution in a variety of *chemistry-inclusive* application areas. Worldwide various laboratories, institutes, and even industries have found its novel and profitable use in diverse areas of application such as pollution control and mitigation, material surface modification, in biology, health and healing, nano materials and fabrications, polymers, improved vehicular engine performance, creating steps towards a cleaner and greener environment *etc.* to name a few. "***Tricks of the CP trade***" in diverse multi-phase, *atypical* and innovative utilitarian studies, including some carried out in our laboratory are presented here to sensitize and motivate researchers about this novel theme open for endless exploration.

Keywords: Free radical; Cold Plasma; Multidisciplinary technology

1. Introduction

Initiations of chemical changes as a general rule necessitate energy input in some form. Various forms of energy available and usually employed comprise of thermal, ultrasound, light, UV, X-ray, Nuclear Radiations *etc.*, in addition to typical catalytic and enzymatic supports. While advancing a laboratory study from a successful R&D effort to pilot scales, and finally into industrial production, the preferred energy utilization scenario and its related process efficiency may however get affected due to factors such as the on-site available energy type and the associated economics. Opportunely, in the last two decades, another unique, quite reactive and scalable source of energy has emerged that now allows

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Author's note: *Though written from a Chemistry based viewpoint, nonetheless this presentation is aimed to popularize Cold Plasma and its inherent utilitarian proffer to a wider group of young and not-so-young researchers in their respective area(s) of learning, including those who enjoy the challenges of multidisciplinary progress in Science, Technology and Health. The examples herein need to be taken as random representations and the interested reader is encouraged to delve into the web and other available literature to get suitably updated on prevailing and freshly emerging directions. Finally, the judgment on "friendliness" is left to the reader's imaginations!*

researchers to take fresh looks into their work approaches. Inventive **Cold Atmospheric Plasma** (or **Cold Plasma**, **CP** in short) offers various unique advantages as a "***chemistry-inclusive initiator***" by virtue of its physical and chemical characteristics. **CP** generation or production is uncomplicated and directly scalable as per demand, in addition to being a highly energy efficient proposition (minimal loss) with *easy-to-finance* prospects relatable to any chosen application. **CP** in research and development is found to be freely exploitable for a variety of purposes, wherein it helps to create appropriate or distinctive reaction environment, and consequently its applications have rapidly gained acceptance all over the world. Readers who are not yet familiar with such exploitations in research and development may find this abridged account of **CP** generation and its functional roles in multidisciplinary environments handy. Herein, some rudimentary details on the **CP** based science and its harmonious amalgamations in variety of domains are discussed, with select working examples to highlight its current as well as future innovative potentials in widening spheres of human activity.

2. *Free Radicals* and the Energy Unit of *Electron Volt*

For effortless perception of the following text it is necessary to get unambiguously acquainted with two simple terms, namely ***Free radical*** and ***electron Volt***. ***Free radicals***, as defined and noted in the ***IUPAC Gold Book*** [1] are atomic or molecular entities that have free or unpaired electron spin. These are represented (with superscript *dot*) as Atom$^{\bullet}$ or Molecule$^{\bullet}$ and may have electric charge, or be neutral. Typical common examples are hydrogen atom, H$^{\bullet}$, mono-nitrogen oxides such as NO$^{\bullet}$, $NO_2^{\bullet}$, methyl radical, $CH_3^{\bullet}$, superoxide anion, $O_2^{\bullet-}$ *etc.* Very familiar hydrated ferric ion $Fe(H_2O)_6^{3+}$ would fall in this category and may be visualized as $Fe(H_2O)_6^{\bullet 3+}$ though in general practice the superscripted $^{\bullet}$ symbol is always omitted. Molecular oxygen needs a special mention here, it being a ***biradical***, $^{\bullet}O_2^{\bullet}$. More importantly though, the chemical reactivity of most ***Free radicals***, especially the small sized ones, fall in the *ultrafast* regime (meaning almost every diffusion controlled collision results in a product formation, therefore such reaction time scales remain in nanoseconds). Some details of ***Free radicals***' chemistry are presented later.

In science, ***Electron Volt*** is a frequently discussed and adopted measure of energy, especially in the field of Photochemistry, Nuclear radiation induced chemistry, **CP** chemistry *etc.* One ***electron Volt*** is the amount of *kinetic energy* gained (in vacuum) by a single unbound electron when accelerated by an electric potential of 1 volt. The numerical value of one ***electron Volt*** (represented as **eV**) is 1.602×10^{-19} Joules (SI unit). Typically, UV photon of 310 nm wavelength energy is 4 eV. (For comparison, one 100 watt incandescent lamp uses 360000 joules or 2.25×10^{24} eV energy.) In the subsequent presentation this unit of energy is used.

Table 1: Assorted Energies in *electron Volts*

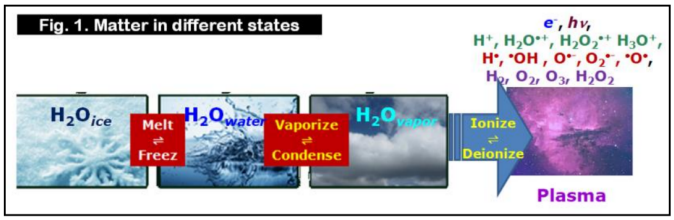
Room temperature average thermal energy of a molecule	~ 0.04 eV
CO_2 laser photon (10.6 μm)	~ 0.117 eV
Other photons (a): Visible / 100 nm UV (UV-C)	1.5 - 3.5 eV / 12.4 eV
(b): Hard UV/ X-rays / Nuclear γ-	12.4 - 124 eV / 124 – 124 keV / ~ 1 MeV
Dissociation Energy: CH_3CH_2-H $\rightarrow$ $CH_3CH_2^{\bullet}$ + H$^{\bullet}$	4.4 eV
Ionization energy of Helium	24.5 eV
Ionization energy of Argon	15.8 eV
Ionization energy of Hydrogen/Oxygen atom	13.6 eV each

In **Table 1** energy of various sources and few physicochemical processes are shown as a handy reference for the discussion below. Extremely high energy content, as in nuclear, X-ray, hard & vac-UV allow each photon to cause multiple electronic excitation, bond dissociation, structural defects, ionization, *etc.* in any target during the course of interaction, including creation of a variety of highly reactive ***Free***

radicals in *ultrafast* timescale of nanoseconds. On the other hand, less energetic visible and IR photons mostly give rise to electronic, vibrational, and rotational excitations, however may even be employed for chemical bond cleavage under favorable conditions (multi-photon events with LASER).

3. Plasma

The oft used word ***plasma*** in Biology and Physics define vastly dissimilar entities or systems; hence its use calls for a description of the area of its existence. Plasma in Biology and Medical Sciences is the fluid fraction of the blood. Although a new physical state was first identified in laboratory by Sir William Crookes in 1879 as "*radiant matter*", half a century later in 1928 Irving Langmuir described this highly energetic physical state of matter as "Plasma" by borrowing the term. When excessive energy gets rapidly pumped into the gaseous atoms or molecules, these consequently lose a fraction of bound electron(s) into free or unbound state, with simultaneous formation of cation(s). The gaseous state then transforms into a new ensemble of ionized entities, as shown in **Fig. 1** for water. It happens with simultaneous formation (high fraction as ***Free radicals***) of variety of cationic, anionic, and other neutral species; their inter-reactions too cause formations of electronically excited species, and new molecules. Diverse physical processes are known to give rise to the plasma state of matter; some of these include use of intense and rapid heating, strong electromagnetic field, electrical potential difference, intense photon density from LASER *etc.* Amongst these, a common and simple method for plasma creation within any gas *at or near atmospheric pressure* is by an *electric discharge*. In a simplified description the essential details are as follows.



4. Plasma near Atmospheric Pressure

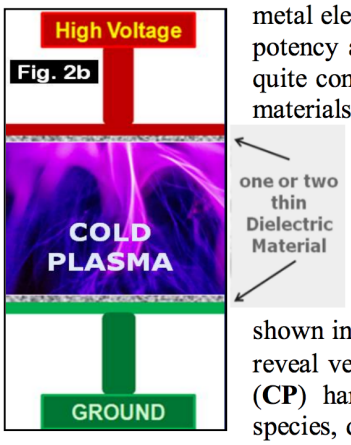
It needs to be noted that the background cosmic rays and natural radioactivity *continuously* and *randomly* generate of ion pairs (freed e^- and $Cat^{\bullet+}$) in our surrounding atmosphere or in any other gaseous medium. Typically, the steady-state concentration of such ion pair is a very low, ~ 10^3 – 10^4 m^{-3}; as older ion-pairs get neutralized or trapped and lost, simultaneously new ones are generated independent of the previous events. In this scenario, as presented in **Fig. 2a**, if appropriate magnitude potential difference (few kV mm^{-1}) is applied between two separated points or surfaces inside a gaseous medium, the freed e^- being very light as compared to any $Cat^{\bullet+}$ generated, gets suitably accelerated towards the anode (+ *ve* charged electrode surface), and may gain sufficient energy during its flight to ionize more intervening atoms or molecules on collision, producing e^- multiplication or an avalanche within 10^{-12} - 10^{-9} s time scale (Townsend multiplication). Under supportive conditions the avalanches sustain to create a visible electric discharge. Parameters that play crucial role include the *Prevailing Gas Pressure* (*near atmospheric pressure as discussed here*), Magnitude of *Applied High Voltage*, Inter-electrode *gap*, Electrode *shape* (curvature), Nature *of Gas etc.* Thus, continuous current flow (for time scale 10^{-9} s and slower, and persist for the period the potential difference exists) may ensue between the two electrode surfaces.

Subtle differences in *electrical breakdown* of gases differ due to: (*i*) Dissimilar electron-impact ionization processes in Atoms or Molecules due to Internal Energy Partition dynamics, defined by the constituent atom *Electronegativity*, *Ionization Potential etc.* (*ii*) At atmospheric pressure lower than normal, fewer ionizations per unit volume happen due to longer *mean-free-path*, causing insufficient

multiplication. On the other hand, at higher pressure the *mean-free-path* gets shorter, but more frequent collisions cause a loss of high fraction of kinetic energy in thermal processes (as sufficient energy to cause next ionization may not be gained by the accelerated e^- before its premature collision). In effect, in either case higher breakdown voltage may be mandatory. Typical breakdown voltage values *at atmospheric pressure* for various common gaseous media are: **Ar 1.73 (kV mm^{-1}), He 1.56, N_2 2.51, H_2 2.73, Air 3.4, N_2O 4.2, CO_2 4.3, O_2 4.5**. In addition to the physical mode of electron multiplication mentioned above, a fraction of the freed electrons (and small fraction of cations) chemically interact with neutral or other ionic species present and produce electronic excited species, atomic clusters (both charged or neutral), anions (by electron capture, mostly if strong electronegative atoms such as oxygen, fluorine are present), and may also cause fragmentation of some molecules present (*typically organic*). Some of the electronic excited species created inside the ensemble decay in ultrafast time scale emitting copious amounts of *em*-radiation covering the range of IR to UV-C, always giving the plasma an intensely bright appearance. Well known examples of such plasma are (a) lightning bolts we observe during thunder storm and rain, (b) a welding job, (c) an electric spark near live wire, *etc*. Thus, following breakdown of medium resistance as described above, free and rapidly increasing flow of current occurs as long as the potential difference holds, and an arc-like random electric discharge may develop. The medium may break down completely, allowing uncontrolled and very high current flow (reaching 10^n ampere) within the plasma zone, causing ionic density to rapidly approach very high fraction. The plasma thermal condition inside may reach extremely high degree Kelvin (billions of degrees inside stellar innards, few hundred thousand inside lightning bolts, few thousand degrees within welding arcs), creating the well known condition of **Hot Plasma**. The average *electron temperature*, e_T (>> 10^{3+} K) in **Hot Plasma** almost equals other *ion temperatures*, i_T (and also equals constituent *gas temperature*, gas_T and boundary or *contact surface temperature*, cs_T; the subscript $_T$ refers to the respective ***kinetic temperature***, *e.g.* 1 eV value of e_T = 11604.5 K (from the relation 1.602×10^{-19} J / 1.381×10^{-23} J/K, taking into account the Boltzman constant, k_B = 1.381×10^{-23} J/K). Thus, Hot Plasma is frequently referred to as "**Equilibrium Plasma**" due to the thermal equilibrium amongst various constituents. However, unlike Physicists and Engineers, for researchers aiming for chemical and biological applications, **Hot Plasma** is not a preferred direct energy source, as material identities may get lost and particles like electrons, protons, cations *etc.* may prevail within. *Therefore, is it possible to tinker with and manipulate such an energetic environment, and tone down to conditions conducive for Chemistry and Biology?*

5. Storyline of Cold Plasma

In the context of high voltage driven electric discharge discussed in **Fig. 2a**, it was beneficially observed that when one or two thin layer(s) of any ***dielectric material*** is/are interposed between the two metal electrodes, the resulting current flow, and consequently the electric discharge potency are significantly reduced to mild levels, and the resulting effect emerges quite conducive for carrying out controlled chemical reactions. Standard dielectric materials include glass, quartz, mica, alumina *etc*. The applied high voltage now charges the exposed surface area of dielectric attached on metal electrode to an *almost equal* magnitude. It may be noted that within the dielectric material its constituting molecules only get electrically polarized, and free passage for electric current through its bulk material gets barred. As a result, the overall circuit current flow gets restricted to the μA to mA range, and only very mild and controlled electric discharge occurs. As shown in **Fig. 2b**, the plasma thus created remained "**Cold**", and its characteristics reveal very low extent of contents' ionization (≤ 2%). The resulting **Cold Plasma** (**CP**) harbors various types of oxidizing and reducing atomic and molecular species, due to occurrence of large number of reactions within (described below in detail). It may be vital to note that various **CP** constituents do not attain thermal equilibrium, and only the



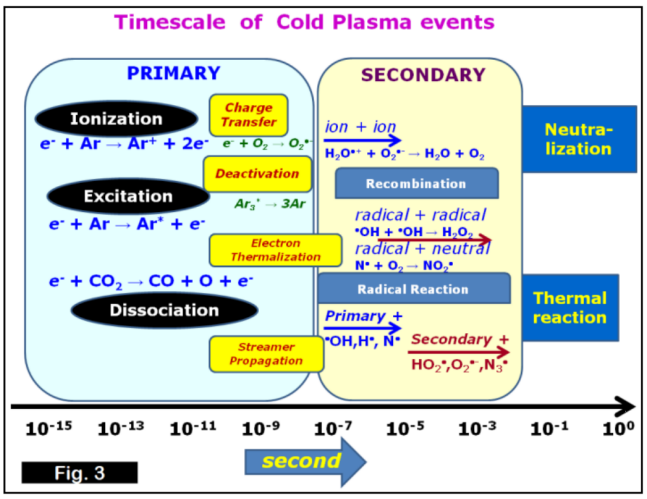
electron temperature, e_T attains high levels (> 10^{3+} K). On the contrary for bulk constituents, *i.e.* the $i_T \approx gas_T \approx cs_T$ (~ 10^2 K) remain << e_T. Thus, **CP** is also known as ***Non-equilibrium Plasma***, ***Atmospheric Pressure plasma, Dielectric Barrier Discharge Plasma*** *etc.* (*Although* ***Cold Plasma*** *generation is also possible employing very different technology of radio frequency and microwaves, such set ups need pertinent generation facilities, frequently limiting their common or ready accessibility and applicability for interdisciplinary and in specific basic research use. Therefore, these plasma generation methodologies are not discussed here*)

Table 2: Typical **CP** constituents produced in various gases near atmospheric pressure

Gas →	CP constituents
He	$h\nu$, e^-, He*, He_2*, He**, $(He)_n^{\bullet+/*}$
Ar	$h\nu$, e^-, Ar*, Ar_2*, Ar_3*, $(Ar)_n^{\bullet+/*}$
N_2	$h\nu$, e^-, $N^\bullet$, $N_2^{*/**}$, $N_2^{\bullet+}$, $N_2^{\bullet+*/**}$, $N_3^\bullet$
O_2	$h\nu$, e^-, O, $O^{\bullet-}$, $O_2^{\bullet-}$, O_2, O_3
Dry air **99% $N_2 + O_2$**	**Primary** = $h\nu$, e^-, O, $N^\bullet$, $N_2^{*/**}/O_2^{*/**}$, $N_2^{\bullet+}/O_2^{\bullet+}$, $O_2^{\bullet+*/**}$/ $N_2^{\bullet+*/**}$ **Secondary** = $O^{\bullet-}$, $O_2^{\bullet-}$, N_xO_y, O_3
Humid Air **99% $N_2 + O_2 + H_2O$**	**Secondary** = H_2O_2, $HO_2^\bullet$, $O_2^{\bullet-}$, HN_xO_y ***etc.*** in addition to some of the above
CO_2 in moist air, **99% $N_2 + O_2 + CO_2 + H_2O$**	**Secondary** = C_xO_y, HCHO, C_2N_2 ***etc.*** in addition to some of the above
Few % H_2O_v in > 90% He or Ar	**Secondary** = $H^\bullet$, H_2, $H_2^{\bullet+}$, $H_2O^{\bullet+}$, $^\bullet OH$,O, O_2, O_3, $O^{\bullet-}$, $O_2^{\bullet-}$ in addition to primary He or Ar related some species as above

Table 2 lists typical **CP** major constituents in various gases. Notice subtle difference related to the nature of species generated in the specific gas employed, mainly due to inherent differences in physical characters discussed previously. The characteristic wavelengths of the light thus emitted also differ amongst different gases used due to the specific and dissimilar de-excitation pathways for various atoms, ions, and neutral entities respectively created. The emitted light wavelengths measured by Optical Emission Spectroscopy (OES) conveniently reveal the emitters' characteristics even in any mixed soup, and help identify the related species present within. Thus, it is quite obvious that utilization of different gases and even mixtures of varying fractions can give rise to numerous possibilities in respect of creation of reaction conditions, either to mimic ones that prevail elsewhere, or explore novel ones. Since He is an expensive gas, relatively cheaper and freely available Ar is frequently preferred in most studies.

Some randomly selected **CP** reactions and respective *timescales of occurrence* are shown in **Fig. 3**. It may be noted here that various time events substantially match the time events observed in the case of pulsed nuclear radiation and LASER light use, and likewise very potent and reactive soup of ***Free Radical*** and non radical species get created. It may be noted that in open atmosphere various primary **CP** constituents from another gas may generate secondary oxygen and nitrogen (**ROS** and **RNS**) species in significant amounts. Therefore, in most cases the subsequent practical **CP** Chemistry falls within the domain of ***Free Radical*** induced and



ROS/RNS mediated changes, and the "***Trick of the Trade***" boils down to appropriate exploitation of the reaction parameters in any intended direction. However, before specific examples are presented, it is necessary to have a detailed look into the experimental **CP** generation tactics, specific design details, and typical associated hardware necessary for successful endeavors. *It may be worthwhile to record here that use of high voltage mandates appropriate insulation of all exposed and conducting points and surfaces, and use of suitable protection gears. Excellent earth line connection is part of the system design that must never be ignored.*

In **Fig. 4**, some selected CP reactor designs are presented. **No. 1** is the most common parallel dielectric plate geometry, already discussed in **Fig. 2b**. Note that the dielectric plates are thin, 1 mm or thicker. The dielectric plate plasma active surface area equals its shared opposite surface area with the metal electrode, attached contiguously without any gap on the back side. The linear gas-gap between the plate surfaces may be less than 1 mm to few cm, and necessitate use of proportional high voltage for medium breakdown. Any kind of sample, such as a flowing gas, or liquid in a container, or solid sample may be arranged or positioned inside this gap for direct exposure from **CP** contents. Design **No. 2** relates to a coaxial or cylindrical surface geometry of the dielectric plates in use, wherein the reactant(s) in a flowing gas passes between the two dielectric surfaces (inner surface of the outside metal coated dielectric and outer surface of the inner metal coated dielectric). While liquid samples would need special protocols to handle, solid samples are conveniently accommodated within the gap. Typical use of this generator geometry is found in ozone production (for almost last one and half century, presented later). Design **No. 3** highlights utilization of a single dielectric plate. In this plane geometry two electrically separated and parallel strips of metal are coated or fixed on one side (bottom as shown) of the dielectric plate, and the gap between the strips is adequately insulated (**I**). One of these strips is connected to the high voltage supply, and the other is grounded as shown. Plasma generation on the intervening area on the top of the dielectric surface allows sample treatment. Furthermore, if the flat dielectric plate is imagined to be rolled into a tubular shape, then the **CP** gets created and contained inside the tube volume as shown. For treatment, samples may be placed within the active plasma zone. However, if need arises then the active plasma may be carried out of the tube and into the open with subtle design modifications, and by maintaining adequate gas velocity. Then sample exposure with the released **CP** jet (alternately called pen, brush, wand *etc.*) is possible at some distance from the active creation zone. This is currently a convenient and oft employed CP source design.

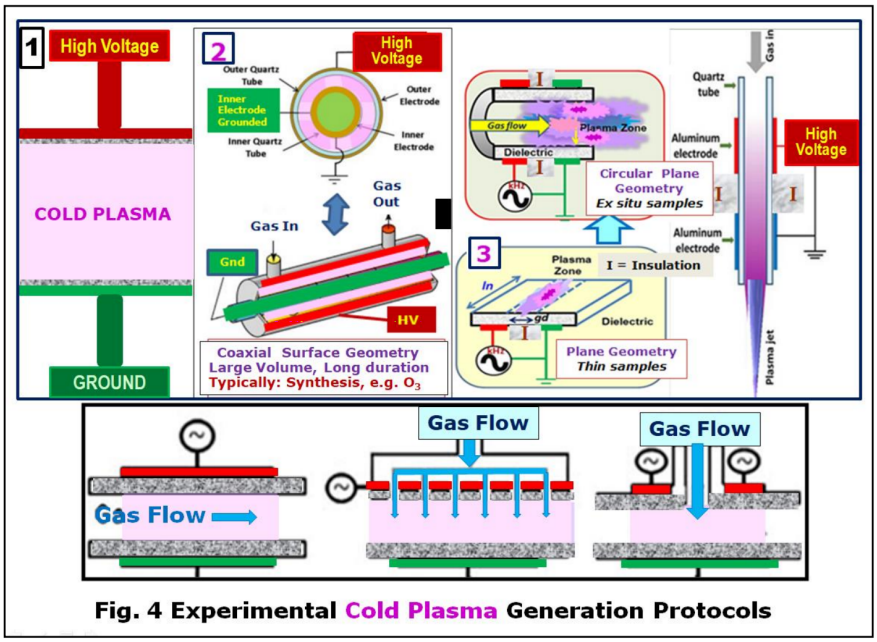


Fig. 4 Experimental Cold Plasma Generation Protocols

In **Fig. 4**, various gas flow arrangements are also shown, which are self explanatory. In some cases the complete **CP** generation system is housed in an enclosure for convenience or safety (especially if some obnoxious product needs to be isolated or handled separately, or for isolating the system from open atmosphere). Since high voltage is an integral part of the set up, appropriate supplies include DC,

AC 50/60 Hz, Pulsed DC, High frequency AC *etc.* types as per need or application. Each type offers different **CP** characteristics suitable for design of specific set ups. While a number of these high voltage supplies are freely available commercially as compact table-top units, frequently these are designed and fabricated in-house if such technical expertise is available. During **CP** experiments in our laboratory, at times we found *em*-interference from such devices onto other electronic measuring instruments or computer placed nearby. To overcome this serious quandary, we designed and developed a portable, table-top **CP Flexible Brush** system (with its dedicated inbuilt power supply) wherein the primary **CP** was locally generated in a quartz tube, then it was "*temporarily extinguished*", but with its "*information of creation*" was carried over a safe distance (6 - 10 feet) through a Teflon tube via a thin copper wire, and made to reignite as a secondary *ex situ* **CP** *plume* on any sample, thus enhancing the device flexibility and its consequent adaptability [2]. Similar complete basic ready-to-use systems may be fabricated or purchased for ₹50 – 100k. In this context, the reader may note that the familiar kitchen gas-lighter enfolds a piezo-electric transducer inside, which on application of pressure produces a spark that ignites the cooking gas over a stove. The spark appears as the transducer generates required level of high electric voltages (kV), sufficient to cause air+gas electrical breakdown. With appropriate modifications, the same transducer has shown its ability for very convenient CP generation in small local volume [3], especially in many handheld, immensely utilitarian devices now available commercially [4].

An example of Argon **CP** plume is presented in **Fig. 5**, to assist readers visualize its physical characteristics and get acquainted with the chemically transforming ensemble over its exposed length. As the narrow and laminar plasma zone exits into the open air from left to right (*e.g.* from a tube as discussed in **Fig. 4, part 3**), it carries primary mono-, di-, and trimeric Argon radical cationic, neutral, and excited species (with some e^-) out of the tip. Upon exit, the surrounding air continuously gets sucked and mixed within the **CP** plume due to high speed of Ar flow (cm to m s^{-1}, at L min^{-1} volumetric flow rate exiting narrow diameter orifice). The **CP** plume contents get transformed (in μs – ms time scale) as chemical and physical interactions generate secondary oxygen, nitrogen, water related atoms, non-radicals, and ***Free Radicals*** (neutral, cationic and anionic nature) partially in excited states. With forward flow, the plume further changes its chemical and physical characters; its shape gets into a turbulent mode and widens considerably. Diminishing plume visibility also suggests that the fraction of light emitting (*electronically excited molecular and atomic*) species survive only for few milliseconds outside the tube. In experiments with large gaps, light emission dies down within a certain distance from the exit tip, and a dark afterglow region results. The chemical nature of the constituents continues to change further as de-excited and uncharged reactive atomic and molecular species, and other ***Free radicals*** are created within. Finally some of these "*chemical contents*" reach any sample placed downstream. Thus, it is quite apparent that factors such as the primary gas flow rate, plasma tube orifice diameter, distance of sample from tube exit, surrounding air composition *etc.* allow the user to design and carry out experiments to employ diverse primary, secondary, or even tertiary chemical initiators of varying reactivity. It may also be noted that replacing the surrounding air (using a suitable enclosure) with chemically different environment help to change the nature and type of secondary species. For example, adding a monomer vapor in argon matrix allow controlled and exclusive polymer coating over a sample surface. The user may even plan sequential or mixed coatings for creating innovative alterations, making this simple arrangement throw up novel ideas and applications. Even by avoiding all extraneous chemicals, in a closed chamber, one may conveniently achieve progressive surface cleaning, otherwise controlled etching, chemical modification,

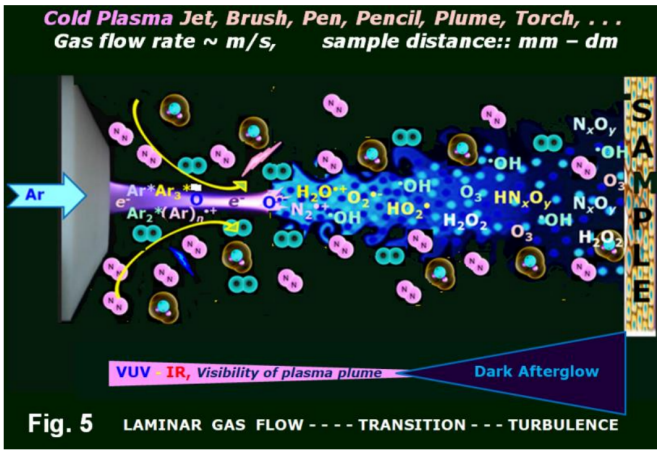


Fig. 5

append alternate *redox* effects, *etc*. Thus, the possibilities are truly endless. Lastly, presence of intense vac-UV and visible radiation of energy 1.5 - 10 eV in the **CP** also allows users to exploit this energy for myriad applications. Following randomly selected studies emphasize the versatility and utilitarian potential of ***Cold Plasma***.

6. CP in Biology and Health

A purist may suggest that molecular level changes in biological contexts are relatable to basic chemical and physical steps. Thus, one may wonder if **CP** *Physics & Chemistry* may have any relevance in biology domain. The classic book "**Plasma Medicine**" by *Fridman and Friedman* published in **2013** (Wiley) amply provides wide ranging answers, all in the affirmative. More recently, a review suggest that continuing basic research remains essential to improve, optimize, and enlarge the spectrum of safe medical applications of **CP**, and also monitor and control plasma treatment and its effects [5].

Humans face seven most common biological enemies in everyday life which are sources of variable trouble. These include **virus, bacteria, mold, pollen, various chemical pollutants, dust mites and pet dander**. We are already aware that **CP** is able to continuously provide **ROS, RNS** and other types of ***Free Radicals*** and intense UV-vis light at the flick of a switch. In this scenario, some recent examples below are intended to motivate readers to further explore, seek answers, and realize the true potential of **CP**, or even contribute actively to find new cures in this ever changing world.

Currently the most discussed virus, SARS-CoV-2 in its various avatars has put the world in a topsy-turvy mode. Thus, the prime search is for a suitable **CP** counter action to tackle this situation. The answer is YES, and seemingly quite potent! For example, the UCLA group has recently demonstrated that the virus is killed with **30 seconds** of CP assisted disinfection treatments on various types of surfaces, **including plastic, metal, cardboard, cotton from facemasks,** and even rough and wrinkled **leather surface** on basketball, football and baseball [6]. Similarly, the Max-Planck Soc. in Germany in collaboration with Terra-Plasma Medical has modified a previously developed hand-held device for chronic wound treatment into a direct application **CP** mechanical ventilator for ***SARS-CoV-2*** *patients* [7]. On another front, next generation of protective masks are under development at the University of Michigan, which aims to harness the power of CP into a small **headset that both blocks and neutralizes airborne pathogens** (including virus) thus allowing free movement of the wearer [8]. Researchers at the University of South Australia have demonstrated that an "*Enhanced* ***Cold Plasma*** *protocol*" that otherwise helps to eradicate antimicrobial-resistant bacterial infections in diabetic foot ulcers, *also* ***significantly reduces SARS-CoV-2 viral load*** [9]. Their strategy to utilize **CP** based "on-demand" amplified antimicrobial formulation comprises of a rich mixture of highly oxidizing molecules: peracetic acid, hydrogen peroxide, and other reactive species such as Tetraacetylethylenediamine and Pentaacetateglucose as antimicrobial precursor acetyl donors, which amplify the antimicrobial effects of **CP**. Thus, not only the targeted virus, but a host of other bio-active enemies can be quickly and effectively neutralized with innovative on site production and utilization of **CP**. With such success **CP** has opened up vast arena for research on its all round antimicrobial potency and creation of more future technologies for exploitation. *A large number of publications await like thinking readers perusal*!

The major health concern otherwise for many decades has been Cancer in its various forms. In this context, Nuclear Radiation sourced from either ^{60}Co radiotherapy machines, *e.g.* **"Bhabhatron"** developed in our country, or dedicated accelerator based devices for targeted treatments, and also from use of specific radioisotopes is well known. It is therefore pertinent to inquire if **CP** can mimic and contribute likewise in a complementary mode. On an affirmative note, more than a decade ago in 2011 pioneers in this ***field*** revealed the "***possibility of a paradigm shift in cancer therapy***" with **CP** [10]. Research carried out then found enormous potential to transform and enhance the available treatment technologies by deploying dedicated **CP** devices. Thereafter, in 2013 the Max-Planck Institute for Extraterrestrial Physics in Germany reported synergistic effect of **CP** with Chemotherapy on aggressive **brain tumor (glioblastoma) cells**, hailing the combination treatment as a new hope [11]. (*The same institute has also developed a number of table-top and hand-held* ***CP*** *devices to treat and cure Cuts,*

Wounds, Nail fungus, Ulcers, Bacterial and Fungal Infections). In 2015 it was revealed that the assortment of **ROS** and **RNS** type ***Free radicals*** were readily participating as potent weapons against Cancer, thus emphasizing their role and importance of appropriate physical exploitation of chosen chemical processes at nano-micro levels on site [12]. In 2019 an exciting and long anticipated development from Purdue University thrilled the world, probably ending any skepticism and waiting [13]. It revealed a "**New CP apparatus to Kill Cancer Cells in the Colon"**. The "*Caandy Helois **CP** Scalpel*™" to remove microscopic cancer tumors remaining from surgery has been approved by the US FDA for first-ever use in a clinical trial. Further research in this direction continues [14], and it is hoped that the above short account would motivate readers to further explore, and may be participate and exploit, to achieve more such excitements with **CP** applications.

Hand sanitization activity prior to 2020 was habitually limited to frontline medical workers and some others in specific jobs. It was mostly ignored by the common populace worldwide. However, in the last two years this activity holds new found importance and necessity. Previously, typical hand sanitizers contained chosen chemicals like ***Triclosan, Benzalkonium Chloride, Providone Iodine*** *etc*. It is not unknown though that these non-alcoholic concoctions are not entirely friendly in long time application and use, and are linked to problems like dermal irritation, allergy, and toxicity of various types. With the advent of and late preference for alcoholic sanitizers, especially in the last two years, other types of warnings have simultaneously appeared from FDA as well as researchers [15]. These include symptoms such as headache, nausea, and dizziness after frequent use, especially in closed environs. Suggestions include soap and water being superior to sanitizer; preferably **hand washing if available** needs to be followed, as was a common past practice. In this context however, it is quite revealing to note that **CP** based compact hand dryer cum sterilizer is commercially available since 2013, with the claim of 93 - 99% kill rate against a variety of pathogens tested, within a very short time [16]. Some of other commercially available products for similar usage are presented later. An immense potential to research and develop stand-alone or portable commercial devices for common or targeted use awaits the interested researchers in S&T.

Within the last few decades mobile phones and allied devices have become our inseparable friends. Following wide variety of user activities these are constantly exposed to biological entities released in user proximity, and also by close contact with other surfaces *etc*. as the user travels and rests. Even presence of fecal contaminants is not unknown. No wonder it is believed that "*The mobile phone not only remembers telephone numbers but also lack of personal hygiene and types and history of physical contacts*". More recently it is believed to be a forgotten or ignored *carrier-source* of ***SARS-CoV-2*** virus [17]. **CP** once more has proved to be quite usable in this regard, and back in 2015 an efficient "**mobile sanitizer**" was successfully researched, which revealed a 10 min treatment with very potent $^{\bullet}$OH radical laden **CP** environ was sufficient, without affecting normal phone operation in any manner [18]. Further efforts in future are expected to turn out pocket-friendly units, *ca.* a mobile case with added piezo-electric based **CP** generation as per specific user need.

Other related developments include creation of **CP** devices and machines for applications in Dentistry to carry out Restoration, Treat Oral Infections, Teeth Whitening *etc* [19]. The active Free Radicals and other species in such use are reported to be $^{\bullet}$**OH,** ^{1}**O**$_2$**, O,** $O_2^{\bullet-}$**,** $NO^{\bullet}$**.** These are currently awaiting FDA clearance. In the author's laboratory a simple Ar gas based handheld **CP** Electroporator was developed in 2015 for selective introduction of extraneous matter (DNA or drugs) into cell through partially opened cell walls, followed by its self repair. It was observed that the same arrangement could be profitably employed to kill *E coli* if so desired.

Thus, inactivation of microorganisms within a short time by non-reversible chemical destruction of cellular macromolecules including DNA has been the "*trade-trick"* in Sterilization, Treatment and Healing of infected and chronic wounds, ulcers and burns, Increased coagulation of blood, Biocompatibilization of surfaces, Aesthetic and ophthalmology applications, Selective inactivation of cancer cells and healthy cell regeneration. It is vital to note that unlike Nuclear Radiation treatment, the patient is never exposed to any radiation. Additionally, during **CP** treatment electricity does not flow through the skin or body. The operators of such devices or machines also do not face any risk for health.

Other hallmarks of simple and controlled **CP** usage are low cost of installation and process management, markedly reduced treatment times, and absence of chemicals. The world over R&D scenario currently reveals a healthy effort in all round development in this area.

7. CP in Chemistry research

Researchers who choose to remain engaged in pure Chemistry domain may be encouraged by the following randomly selected examples. Herein divergent possibilities for adoption of **CP** in their daily work are highlighted: (a) Production of 10 - 100 nm sized *iron nano particles* from ferrocene in alcohol solution at minimal cost and effort was achieved in a reductive environment offered by pure Ar **CP** jet, for products' potential applications in water purification, special magnetic micro- and nano-electronics usage [20]. (b) Graphene-supported *palladium nano-catalyst* (~ 50 nm) was conveniently made with **CP** for hydrodesulfurization of carbonyl sulfide (COS) in coal gas [21]. Almost 25 times enhanced catalytic activity was observed compared to Pd supported on activated carbon or Graphene-supported palladium composite prepared by conventional reduction process. (c) Creation of High-performance *Platinum nanoparticle* embedded TiO_2 photocatalyst for dye degradation [22]. The process involves simple steps like mixing H_2PtCl_6 solution with nano TiO_2 suspension for 24 h, followed by drying at 100 °C for 2h, and sample treatment in reducing **CP** of Ar and H_2 mixture. The TEM of 1.5 wt% Pt/TiO_2 suggests formation of ~ 100 nm sized catalyst, and almost 25 times enhancement in its activity. (d) First time report from author's lab of a simple and efficient *one-step conversion* of few thousand ppm aromatic *benzene* to exclusive *aliphatic compounds* such as *(i)* methane (~ 50% without catalyst, and exclusive generation with added H_2) or *(ii)* ethylene (with packed TiO_2 coated catalyst within the **CP** generator, **type-2** in **Figure 4**), both in moderately flowing Ar gas [23]. (e) On-line transformation of abundantly available *C1 to C4 light hydrocarbons* (mostly methane) into usable liquid fossil fuel (*petrol or gasoline*, C5 to C12, and *diesel*, C12 to C20) was achieved in a single step with **CP** in combination with **Solid Oxide Electrochemical Cell** [24]. The latter assisted in minimizing radical recombination reactions, eliminating formation of undesirable products. The other byproduct was water (no CO or CO_2 formed). A web search for similar exploitable and novel **CP** use and applications in the field of Chemical science and technology reveals a rapidly exploding number of studies, with significant simplification of reaction designs with reduced number of steps, dip in energy usage, avoidance of unnecessary chemicals and solvents in specific cases as is preferred or desirable for a "green technology".

8. CP for Improvements in Environments' Quality

Presentations so far amply suggest that the **CP** approach has the ability to contribute significantly in cleaning up of our environments, that have been irrationally and uncontrollably been allowed to degrade with time. In this section the current scenario is reviewed.

Fig. 6 summarizes the various reactive cleaning steps and process offered by **CP** presence. All unacceptable entities are taken care of by one or more of the four distinct steps, not necessarily in any particular order or sequence. Random studies, processes and products are summarized below for a closer look at the level of development over the years.

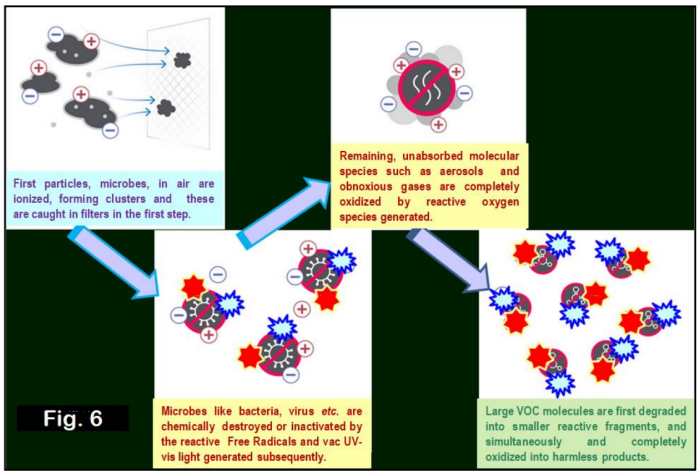


Fig. 6

(a) **Indoor CP deployments:** In

a recent study, inactivation of indoor airborne viruses is reported with use of a glass bead packed bed **CP** reactor (type-**1** in **Fig. 4**) [25]. A disposable filter near the exit removes all leftover particulate material. At a high air flow rate of 270 Lpm, the device works continuously to purify air by 3 orders of magnitude. Imagine such devices placed in your laboratory at strategic locations; mountain fresh air may be available to you with just the flick of a switch! Of course, more than one commercial product is already available in the international market, including India for suitable purification of indoor environments; these also include small portable ones for travelers for use in cars as well as hotel rooms, to larger model for fixed use in larger homes, rooms, schools, hospitals *etc* [26].

(b) Typical examples for **outdoor CP deployment** (very large capacity systems) presented below were researched and developed for specific purposes. (*i*) A 510 MW_{elec} coal-fired thermal power plant in USA is reported to utilize a three-stage process that includes a **CP** reactor, followed by a combination ammonia scrubber and absorber unit to neutralize and absorb the various acids formed; and finally, a wet electrostatic precipitator to remove the mists and aerosols [27]. Consequent reduction achieved for various species are as follows: SO_2 - 98 %, NO_x - 90 %, total Particulate - 99.9 %; Fine Particulate - 95 %; Mercury - 80 -90 %. (*ii*) A patented Gas Phase Cold Plasma (GPCP) reactor was designed and developed at the Pacific National Laboratory, USA as a cost-effective and environmentally friendly alternative to the prevailing thermal removal of lethal pollutants and volatile organic contaminants (VOCs) from gas streams [28]. Reported destruction efficiency therein of various hazardous air pollutants as well as *chemical and biological warfare agents* are as follows: Trichloroethylene > 99.9%; Perchloroethylene > 99.9%; Benzene 97.85%; Naphthalene > 99.9%; GD nerve agent > 99.8%; Hydrogen cyanide > 99.4%; Cyanogen > 99.8%; Methyl cyanide 98%; Phosgene > 99.84%; Methane > 97%; Freon14 ~ 70%; Phosphonofluoridic acid > 99.8%; and Dimethyl methyl phosphonate > 99%.

(c) **Potable or safe and clean water** is already a luxury at various locations and countries on our blue planet earth, mainly due to rampant exploitation of pristine natural resources and additional pollution from numerable sources. **CP** based solution in this direction is constantly getting modernized. In the distant past Chlorine was the gas of choice for water treatment. However, it was realized that Cl_2 gas is less powerful for micro-organisms, useless against chemical contaminants, and in presence of certain polluting chemicals may form carcinogenic trichloromethanes and chlorinated phenols. Thus, its deployment was eventually replaced by ozone, O_3 generated onsite from air or oxygen. The reactor design **Fig. 4**, no **2** has been the mainstay for **CP** based O_3 generation, which is safe, cheap, and one-step process controlled by the flick of a switch, and needs only minimal human intervention in the form of maintenance. No wonder, world over the current estimate of O_3 production for water purification may be higher than 10^{12} ton yr^{-1} (~ 32×10^3 ton s^{-1}). Ozone destroys bacteria, viruses, spores, mold and algae, also oxidizes most harmful chemicals such as dyes, insecticides *etc*. It is well known that excess O_3 quickly decomposes into O_2 in air and as H_2O_2 in water, and finally into H_2O and O_2. Various small and portable table-top O_3 generators are commercially available for vegetable, fruit cleaning at home and elsewhere. In such cases the dissolved O_3 itself, or its daughter product in water, mainly the ***Free Radical*** ˙OH efficiently completes the intended clean-up job. (*All users of ozonizers need to note that ozone at ppm level is harmful, hence its release inside a closed room needs to be strictly avoided. Instead, such use may be practiced only outside in open air, away from human activity.)* More recently however, it has been reported that stubbornly resilient and toxic Poly- and perfluoroalkyl (PFAS) compounds, sometimes found in contaminated drinking water (*from over use of Teflon type coatings on kitchenware followed by its slow degradation*) are not decomposed and removed by O_3. For hassle free and successful removal of such chemicals, another innovative **CP** technology has been successfully researched [29]. It utilizes a ***semi-hot* Plasma**, first created is flowing air, that is directly injected into the contaminated water inside a reaction chamber. The suitably transformed **CP** with its "*afterglow reactive chemicals"* (Refer to **Fig. 5**) destroy all the *otherwise impossible to destroy species* present. Very recently, a commercial water purification product has appeared in the market that claims a paradigm shift in "*oxidative water treatment*" [30].

Thus, **Cold Plasma S&T** allows Environmental Remediation at low cost, with on-site usability, and is capable of running on solar energy, with minimal equipment complexity, is immensely exploitable

and locally modifiable for chemical degradation and total removal of pollutants such as: *VOC*s (volatile organic compounds including carcinogens, hazardous gases, harmful coloring agents and chemicals, bacteria and allergens (in humid and aquatic waste), particulates (such as aerosols), obnoxious odor (emanating due to presence of aldehydes, ketones *etc.*, H_2S (sewage or industrial), NO_x and SO_x (fossil fuels' burning and other industrial sources), and dust mites frequently found indoors. **CP** thus appears to have endless abilities!

9. CP in Material Surface Changes and Improvements

Cold Plasma being a surface-active contrivance, its convenient exploitation on solid samples and materials as per specific requirements has been wide spread. In **Fig. 7** various modes of **CP** assisted surface treatment are shown, which are self descriptive. Some random studies covering a wide range of aims and objectives are discussed below. In the domain of "New or extra *functionalization* of **Textiles**' Surface(s)" diverse range of materials were treated to add explicit surface properties. For example wool, nylon, polyester fabric surfaces were altered to *hydrophobic* (water repelling) type from *hydrophilic* (water attracting) type with precursors such as styrene, butadiene, and dodecylacrylate put in **CP** created from different gases [31]. Similarly, properties like absolute hydrophobicity, color-latching, superior appearance and feel with crease control, fire resistance, controlled porosity, anti-microbial character *etc.* were incorporated by treating fabrics with **CP** of air, O_2, Ar, F_2, He, CO_2 or mixtures. Quite interestingly the **CP** technology could be employed to manufacture "dual functionality" fabric, *hydrophobic* on one side and *hydrophilic* on the reverse [32]. Creation of *self-cleaning* cloth may get a boost with the use of **CP** technology.

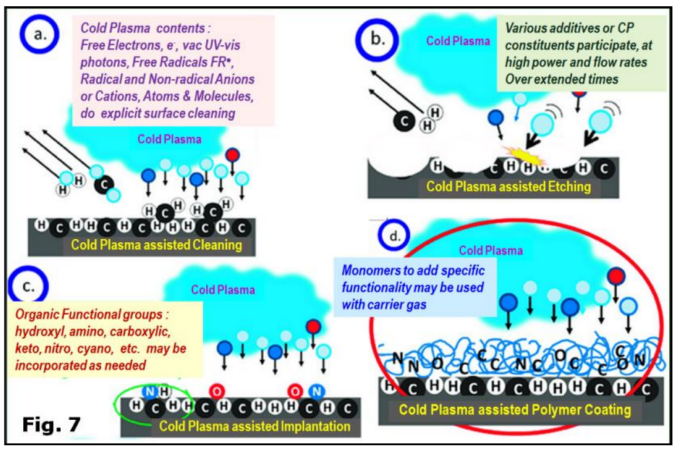


Fig. 7

Wood, with complex organic nature, is similarly amenable for surface chemical modifications. It is no wonder that the **CP** treatments have been extensively used to chemically modify wood and derived timber surface [33]. Superior finish and facile adhesion of surface polymer composite layer (wood-plastic combo) was thus achieved. This treatment method minimizes fungi growth and termite attacks, and also helps to incorporate surface water and scratch resistance characters. A clean wood sample, *e.g.* a finished bathroom door, moving on rollers, is sprayed with a chosen liquid monomer and immediately exposed to **CP** at 360° geometry. The results are instantaneous and long lasting. (*Similar results had also been achieved employing Nuclear Radiation; thus **CP** acts as a mimic, but comparatively at token strain on resources and pocket*).

Similarly, chemical creations of new and exotic surfaces were also achieved. In a study to design photocatalytic, self-cleaning, and anti-staining *Super-hydrophobic* surface, a required ***nano particle*** + ***nano composite*** combo surface coating could be effortlessly achieved using a dispersed aerosol of oleate-capped ZnO in n-C_8H_{18} in flowing He gas **CP** [34]. The coating combined the chemical characteristics of both the NPs and the organic component, which originated from the plasma polymerization of *n*-octane. In another study, **CP** assisted liquid deposition of -CF_2-CF_2- group on various substrates such as cotton, polyester, polypropylene, nylon *etc.* using liquid aerosols helped to create an oil, water and alcohol repellent (~100%) surface coat [35]. Similarly, powder deposition technology has been patented that employs **CP** in combination with dispersed nano powder to create a nano-porous nano-structured ceramic surface coating of 10 nm – 10 μm thickness [36]. In author's laboratory, a simplified surface cleaning process was developed for *Silicon Surface Barrier Detector* prior to its fabrication (*for use in **Nuclear***

***Radiation** detection*), with use of 90% Argon and 10% air based **CP** for 3 min [37]. The methodology helped to reduce detector operational leakage current substantially, as compared to the ones fabricated following conventional methods. Thus, the approach of surface cleaning and modification with **CP** for few min in various application areas is not only quite innovative, but also quick, cost-effective and eco-friendly. In summary, some of its salient features include (1) Mostly in a Single-step, solvent free approach; (2) Deposition of organic, inorganic, nano-composite, nano particle coating possible (e.g. polymer, silica-like coating, anti-scratch films, ceramics *etc.*); (3) Typically polymeric package materials may be suitably modified by increasing the surface energy to facilitate gluing and to improve printability, avoiding the need of using a primer, and promoting coloring (dyeing); (4) Improvement of mechanical properties, added *hydrophilicity* or *hydrophobicity*, reduced shrinkage, *etc.*; and (5) Surface or Interface cleaning. *In this context, it may therefore be a logical and appealing proposition to try and test if diamonds' surface get colored from application of controlled surface defects by **CP**, and thus mimic Nuclear Radiation, which is currently in use for creation of artificial (bulk volume) color in high-demand commercial diamonds.*

10. CP in Food Technology and Related Applications

It needs to be stated that in our country (and elsewhere) for many decades Nuclear Radiation technology is being widely and effectively employed in *Radiation Processing of Food Items* [38]. Consequently, the treated food items become pathogen and parasite free and gain shelf life, which frequently allow mere chilling in place of deep freezing during storage, and thus help save energy usage. For example, export of local fruits such as mangoes (*to USA*) has become possible. However, a high construction cost, other factors associated with such large treatment facilities, including adherence to stringent safety norms have restricted its universal small and medium-scale appeal.

In the context of **Food Items' Processing and Preservation**, it may be noted that the harmful pathogens, parasites, and pesticides reside mainly on or near the item surface. Hence, **CP** applications, with its rich contents of **ROS/RNS** discussed previously have a direct bearing on such elimination. Examples on use of **CP** treatments include ongoing research in various countries, which provide convincing reports of its local success. Research in the Glasgow University in Scotland in 2013 revealed that various items inside a sealed package or non-metallic container without any additives could be exposed with **CP** [39]. Ozone produced within the package (**CP** type **1** in **Fig. 4**) efficiently destroyed or inhibited bacteria or virus growth that occurred otherwise, thereby sterilizing the contents' surface area uniformly, and helped to extend product shelf-life. Few examples of such treatment include: reduction of pathogens in poultry, healthy bread and muffins. Similarly, in another study revealed that with few min of **CP** treatment, strawberries could be freed of microorganisms [40]. A study from Purdue University revealed similar **CP** treatment helped to extend shelf life of tomatoes by 4 weeks [41]. In 2016 the New South Wales Department of Primary Industries and the Australian Government initiated research studies with **CP** deployment to benefit the growers, processers, packers and consumers of fruits (apple, blueberry, citrus, strawberry), nuts (macadamia, almonds), vegetables (spinach, lettuce, fresh-cuts), aiming to mitigate the food safety risks [42]. In 2018, the Vietnam Institute of Technology has initiated research on the use of environment friendly **CP** technology for decontamination of agricultural products and fresh food and vegetables [43]. Thus, incorporation of **CP** treatments in Food Industry and Technology, as also projected by a currently available commercial system [44a], describes achievable benefits world over such as (a) Increased germination and yields; (b) reduced bacterial levels at harvest, especially with use of **CP** generated nitrate fertilizer; (c) Degradation of various types of pesticides before storage and consumption; (d) Pest and mytotoxin removal; (e) Pasturization and sterilization; and (f) most significantly, anticipated reduction of food wastage [44b].

A recent monograph written and edited by experts in the field, aims at academic researchers, food scientists, and government officials working on disinfection of food products [45]. It unequivocally states that **Cold Plasma**, one of the newest and novel technologies for food preservation, is promising and affordable, waterless, waste-free, and leaves no chemical residue on the products, works as a disinfectant

of food products and packaging materials while maximizing microbial and spore inactivation. Finally, this section would remain incomplete without the following anecdote, from space. In 2001, experiments were funded by **The European Space Agency** to eliminate "*The foul exhaust air from cooking* ***French Fries*** *within the* ***International Space Station***". **CP** did not fail to provide the most appropriate response to this demand. A suitable device was installed that works by using electrons and ***Free radicals*** within the **CP** disc to neutralize odors. The **CP** breaks up the offending molecules into harmless components that do not smell and do not need to be extracted afterwards. The cleaning was found to be almost thousand times faster than the traditional existing chemical method [46] that was replaced.

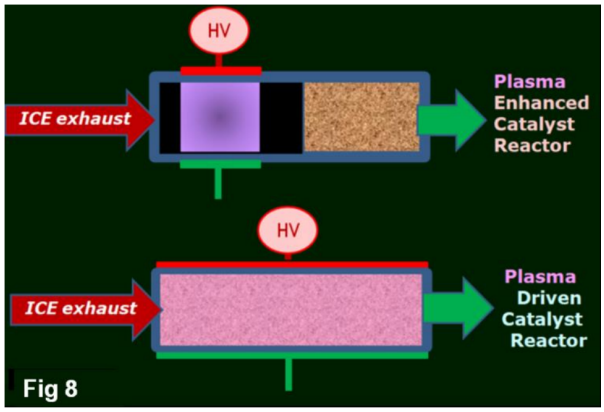
11. CP in Travel and Transportation

In the modern day fossil-fuel driven transportation, a *random* comparison of two passenger car models (of two-door range) made over a gap of almost 113 years, one finds the petrol mileage has barely improved, from reported ***mpg*** of about 24 or 10 km L^{-1} in 1908 to just 30 or 12 km L^{-1} today. Of course, the overall improved getup and looks have never failed to impress. Similar mileages are also ascribed to other makes and models. To realize the prevailing scientific premise, or may be lack of it leading to this conundrum, one needs to peek into various chemical steps that drive the internal combustion engines (ICE), and take a astute look into various transformations.

The fossil fuels employed in ICEs include either Petrol/Gasoline (C_5-C_8 hydrocarbons) or Diesel (C_{10}-C_{21}) with ~ 86% C & 14% H contents. Taking the typical example of petrol, for its complete (theoretical) combustion, *ca.* $\mathbf{2C_8H_{18} + 25\ O_2 \rightarrow 18H_2O + 16CO_2}$, each C_8H_{18} molecule needs 12.5 O_2 molecules to produce 9 H_2O and 8 CO_2 molecules. The existent picture regarding the combustion products are however quite different. The variety of products in tail pipe exhaust, in addition to N_2, CO_2 and H_2O, include: *CO, NO_x, NH_3, SO_x, RH, RR'H, C_6H_6, ROH, HCHO, RCHO, RCOOH, RCOR', RNH_2, $ArNH_x$, PAHs, VOCs, H_xNO_y, $PM_{2.5\ \&\ 10}$, Metals, etc* [47], which suggests the oxidation reaction above remains nearly a fantasy, and occurrence of large number of other unneeded chemical reactions, seriously affecting the anticipated mileage. (*In a related concern, it is no secret that fossil fuel usage contributes towards global warming, and in persistence of localized harsh environmental pollution world over* [48].) A *back of the envelop* random analysis for a car (*with 4 cylinders, capacity 1 L each, with 2 fillings for 1 crankshaft revolution, running at 2400 rpm, at 50 kmph speed and top mileage of 10 km L^{-1}*) reveals an duration of just over 10 ms available for the fuel oxidation, which never allows the reaction to get to completion. Moreover, since HC fuel oxidation needs only oxygen (just 21% of the air), the major 78% N_2 plays no role in it. No wonder, finally all are waking up to this grim realization, and seeking better alternatives. However, it is anticipated that fossil fuel usage may continue for a long and indefinite period, thus appropriate correction in the fuel usage steps have become mandatory, forcing intensive ***D^4*** *(design, development, demonstration, deployment)* in various directions. **CP** is found to play an active role in these applications too, and the following account throws some light on its utilitarian roles.

In the year 2007, research in the **Los Alamos National Laboratory, USA** found that **CP** assisted fuel combustion (CPAC) is indeed a fertile area for R&D. An atomized fuel (RH) stream prior to combustion when passed through a **CP** zone attached downstream to an existing fuel injector, randomly broke down the long chains of hydrocarbons into smaller fragments (*typically at energy input of < 10 eV, each molecules produced neutral Free radicals,* $R^{\bullet}/H^{\bullet}$, *while at > 10 eV various ionic Free radicals,* $R''^{+}/R''H^{\bullet+}$*were formed*). Consequently, not only the combustion was observed to be stabilized, the fuel burning efficiency also enhanced to raise ***mpg*** and reduce pollution [49]. In a related research in 2018, the **Eindhoven University of Technology, Netherlands** in their research dealing with ***Cold Plasma Flame Diagnostic & Modeling*** revealed that the unique nature of Cold Plasma makes fossil fuel combustion leaner and cleaner, and simultaneously minimizes greenhouse gas emissions [50]. In their study a new CP based burner geometry allowed thorough experimental and theoretical investigations of the basic mechanisms, and revealed further optimization was necessary for the complex physicochemical parameters of **CP** flames in varied scales in space and time. Interestingly, at the same time in **Japan** an engine attachment, Plasma Direct™ unit was commercialized and is available for various models of motor

cycles, passenger car and SUV engines running on petrol/gasoline [51]. Placed upstream, it creates variety of ***Free radicals*** in the air-fuel mixture inside the ICE, which modified the combustion to reach all corners of the ICE, producing improved ignition and higher ***mpg*** values, in addition to being environment friendly. In the last few years, **Transient Plasma Systems** in **USA** has developed a number of **CP** based products, including a *Nanosecond Pulsed Power Ignition System*, which allows a number of desired fuel ignition benefits [52]. In summary, **CP** assisted Fuel Reformation and Ignition helps to break down the long chains of hydrocarbons in fuel into smaller fragments, thus reducing the fuel ignition/oxidation time, improving the engine performance by ~ 20%, in addition to the reduced presence of unburned and undesirable combustion products such as CO, NO and NO_2 while utilizing less power than conventional *Spark Plug*. Simultaneous progress in the field of electronics allowed matched generation of nanosecond pulse DC voltage with compact and portable hardware.



The adventure of **CP** use in transportation sector however is not over yet. Keeping in view the world-over demands for a cleaner environment, purification of ICE exhausts with **CP** are also being researched, with appreciable success, and more are on the way. Typically, as shown in the **Fig. 8**, the exhaust gas mixture is treated in a catalytic reactor (CR) chamber placed downstream to the ICE for treatment. Such deployment of **CP** in either of the two arrangements is possible: (i) Plasma Enhanced CR, wherein **CP** generation is sustained in the exhaust gas mixture to chemically activate it prior to the CR, or (ii) Plasma Driven CR, wherein **CP is** generated within the CR volume. For almost two decades, various studies had revealed the benefits of such **CP** use in variety of combinations, configurations, and constant and suitable modifications are in progress [53]. The key benefits achieved so far with CP based ICE exhaust gas treatment include (*i*) Oxidation of leftover or unburnt fuel and consequent reduction of its atmospheric release; (*ii*) Efficient and improved NO_x / NH_3 transformations, mainly to N_2; (*iii*) Applicability to the full range of Diesel and Petrol engines; (*iv*) Efficiency not being affected by sulfur content in fuel; (*v*) Various gaseous species released are N_2 H_2O, O_2, CO_2 even at low temperature operation (cold start), with Plasma system power consumption ~1 kW *vis-à-vis* typical engine power of 60 kW (< 2%). Thus, from fuel input to tail pipe exhaust, **CP** is able to play varied roles, and contribute in multiplicity of improvements in vehicle performance and the surrounding environment.

12. CP Elsewhere and Conclusions

The above presentation reveals various features of ***Free Radical*** mediated science that occur within, and highlight the related ease of system design, handling, use, and applications in a myriad of human activities, directly and indirectly. The story of its *Friendly* nature however would remain incomplete if some other related applications are not highlighted here. These include (a) Sterilization of medical devices on site, which otherwise need to be autoclaved or N_2O treated. The medical devices are sealed into a bag or tray, and placed inside the **CP** device [54]. The device generates O_3 inside the bag to sterilize the device. The sealed packet may be stored prior to use later. Excess ozone quickly decays back to oxygen, preventing any exposure of the user. (b) Printing of μm sized structures using nano inks by combining high-resolution plasma printing with rotogravure printing [55]. (c) Mercury free Fluorescent Light, produced efficiently employing the reaction Xe —CP→ $Xe^{*/\bullet+}$ — Xe → Xe_2^* + $Xe_2^{\bullet+}$, wherein xenon (in neon) discharge emission at λ = 147 & 172nm gets converted to white light with phosphor coating [56]. (d) Similarly, Plasma TV utilizes Xe (in Neon) **CP**, and the three primary colors Red/Blue/Green in pixels are generated with different phosphors [57]. (e) Plasma Clean Room Air

Conditioner, working on the principle of air sterilization and cleaning discussed in the previous section **C** [58]. (f) A new Barrier Ionic Discharge (BID) detector in Gas Chromatograph employs a **CP** in He gas for highly sensitive and hassle free universal detection and analysis of trace organic and inorganic compounds [59]. (g) For effective and quick removal of unpleasant odors from textiles, a portable and small handheld device offers style and comfort at home and during travel, as it instantly refreshes the cloth without washing or deodorants [60]. In essence, the **CP** science and technology has conclusively proved that it quite powerful, versatile, and is able to participate as a ***standalone multidisciplinary approach*** with multitude of roles and applications**.** *Finally, this presentation would be missing the element of fun and wonder without a mention of the* ***multihued, transcendental, ethereal*** *phenomena of* ***Aurora*** *observed in our sky near the poles (Aurora Borealis near North Pole, and Aurora Australis near South Pole). The vivid colors therein are generated by de-excitation of excited oxygen atom (emitting mainly green, some brownish red, yellow photons) and nitrogen atom (blue, red, violet photons) whenever a* ***Giga-scaled CP*** *forms due to ionization of earth's upper atmosphere by charged particles released periodically within the solar wind* [61].

Cold Plasma science and **Cold Plasma**-enabled technologies have significantly revolutionized the modern society lifestyle, and enabled our understanding way beyond the innate processes that dominate the solar activities and the interstellar medium. It is anticipated that with continued stewardship, apt awareness about its universal applicability would bring in further innovative R&D world over, and simultaneously translate into *pan-India* societal benefits and broaden its *friendliness*.

Declaration

This presentation is an updated and focused summarization of the more elaborate talk delivered in December 2021 at the 35th annual conference of the Orissa Chemical Society.

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Scientific Voyage
Vol. 3, No. 1,
Page 19-24 (2022)

SCIENTIFIC VOYAGE
ISSN: 2395-5546

GCECT
Publication
Jan - Mar

Covariant formalism for the Berry connection due to gravity

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Abstract: It is well-known that Dirac particles gain geometric phase, namely Berry phase, while moving in an electromagnetic field. Researchers have already shown covariant formalism for the Berry connection due to an electromagnetic field. A similar effect is expected to happen due to the presence of Gravity. We use WKB approximation to develop a covariant formalism of Berry-like connection in the presence of Einstein gravity, which can be further used to describe the Berry-like phase or simply Berry phase. We also extend this formalism for massless Dirac particles (Weyl particles).Then we further show that this connection can be split into two parts, one of which vanishes when the metric is spherically symmetric and thus can be linked to the Aharonov-Bohm-like effect in the $3 + 1$ formalism. At the same time, the other term can be related to the Pancharatnam-Berry like effect.

Keywords: Covariant formalism; Dirac particles; Weyl particles; Berry connection

1. Introduction

Berry phase is a well-known geometric phase that has been adequately described in the evolution of spinors in the presence of an electromagnetic field. We expect that gravity should also cause a similar effect. Indeed we use WKB approximation for Dirac and Weyl particles to describe a covariant formalism for the Berry-like connection which can be further used to define Berry curvature, and to describe the evolution of the Berry-like phase of a particle as it moves in the presence of gravity. We perform the calculation of this covariant Berry connection for Dirac particles (massive spin-half) and Weyl particles (massless spin-half).

The derivation we perform is based on a previous work [1], where Stone used WKB approximation in the Dirac equation to get the expression for Berry Connection in the presence of an electromagnetic field. We have a similar approach, but we start from the Dirac equation in curved spacetime, where the derivative is replaced by the spinorial covariant derivative. We see that this leads to a significant change in the equations that we get after using the WKB approximation.

Once we have the expression for Berry connection due to gravitational effect, we would see that it can be split into two parts, one of which would vanish in the case of spherical symmetry. We will see that these terms can be defined as Pancharatnam-Berry-like (retained already) and Aharonov-Bohm-like (vanished in spherical symmetry), linking it to the $3 + 1$ formalism of the geometric phase. Earlier it was found [2,3,4] that in $3 + 1$ formalism, during the evolution of spinors in the presence of gravity, we obtain a Pancharatnam-Berry-like and Aharonov-Bohm-like term. Thus we expect the covariant formalism to show similar behavior,

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which we show through our calculations.

2. The Modification to Newtonian gravity

We start with the Dirac equation in curved spacetime. A Dirac field $\Psi(x)$ with a mass m satisfies

$$\big(i\hbar\gamma^{\mu}(\nabla_{\mu}) - m\big)\Psi(x) = 0, \tag{1}$$

where γ^{μ}-s are the spacetime gamma-matrices which are related to the flat spacetime gamma-matrices by $\gamma^{\alpha} = e^{\alpha}_{a}\gamma^{a}$, e^{α}_{a} is the tetrad, the Greek and Latin indices imply respectively curved and flat coordinates, and ∇_{μ} is the covariant derivative of spinors which is defined by a spin connection. The spinor derivative acts on the spinor field as

$$\nabla_{\mu}\Psi(x) = (\partial_{\mu} + \Omega_{\mu})\Psi(x), \tag{2}$$

where Ω_{μ} is defined as

$$\Omega_{\mu} = -\frac{i}{4}\omega_{ab\mu}(x)\sigma^{ab} = \frac{1}{8}\omega_{ab\mu}(x)[\gamma^{a}, \gamma^{b}]. \tag{3}$$

Now we use the WKB ansatz

$$\Psi(x) = ae^{-\frac{i\varphi}{\hbar}}, \tag{4}$$

where $a = a_0 + \hbar a_1 + \hbar^2 a_2 + ...$, also $\partial_{\mu}\varphi = p_{\mu} = (E, -\mathbf{p})$. We consider the equations until the order of h^1 and use them to reach to our covaraint Berry connection.

3. Dirac Particles

This is the case where $m \neq 0$. At the order of $\hbar^0$ we obtain

$$(\gamma^{\mu}p_{\mu} - m)a_0 = 0.$$

Considering u_{α} to be the complete set of eigenspinor solutions of the above equation such that

$$(\gamma^{\mu}p_{\mu} - m)u_{\alpha} = 0, \tag{5}$$

$a_0 = u_{\alpha}(p)C(x)^{\alpha}$ where C^{α} is the complex number.

At the order of h^1, we then obtain

$$i(\gamma^{\mu}\nabla_{\mu}a_0) + (\gamma^{\mu}p_{\mu} - m)a_1 = 0. \tag{6}$$

We would also need the relation for the four-current of Dirac particle which is

$$\bar{u}_{\beta}\gamma^{\mu}u_{\alpha} = \delta_{\beta\alpha}\frac{p^{\mu}}{m} = \delta_{\beta\alpha}V^{\mu}. \tag{7}$$

Using Eqs. (5)–(7) and the completeness and normalization of u_{α}, it can be shown that

$$(\delta_{\alpha\beta}V^{\mu}\nabla_{\mu} + \frac{1}{2}\delta_{\alpha\beta}\nabla_{\mu}V^{\mu} + \frac{1}{2}V^{\mu}(\bar{u}_{\alpha}\nabla_{\mu}u_{\beta} - \nabla_{\mu}\bar{u}_{\alpha}u_{\beta}))C^{\alpha} = 0. \tag{8}$$

Here when we apply ∇_μ to V^μ we are considering the covariant derivative for tensors which comprises of the Christoffel connection. We are using the same symbol ∇_μ for both spnior covariant derivative and covariant derivative for tensor fields. This should not cause any confusion, since the type of covariant derivative can be determined by the object on which it acts on.

Now we can define our covariant Berry connection as

$$B_{\mu\alpha\beta} = \frac{i}{2}(\bar{u}_\alpha \nabla_\mu u_\beta - \nabla_\mu \bar{u}_\alpha u_\beta), \tag{9}$$

which can be used to define berry curvature and to describe the Berry phase that a Dirac particle gains due to gravity. The details of the above derivation can be found elsewhere.

4. Weyl Particles

In this case we consider spin half particles with mass $m = 0$, Thus the Dirac equation for massless particles is

$$\gamma^\mu \nabla_\mu \Psi(x) = 0. \tag{10}$$

We use here Weyl representation for the gamma-matrices to make our calculations easier. We see that this case is significantly different than the last case because, first of all, the Dirac equation does not have $\hbar$, which we used as a parameter in the last case. Hence, we define a small parameter ϵ and expand our solution in terms of that. We further seek WKB solution and choose

$$\Psi(x) = a e^{-\frac{i\varphi}{\epsilon}}, \tag{11}$$

where $a = a_0 + \epsilon a_1 + \epsilon^2 a_2 + ...$, also $\partial_\mu \varphi = p_\mu$ and ϵ is the small parameter. Similar to the case of Dirac particles, we substitute Eq. (11) in Eq. (10) and expand in the orders of ϵ. Considering terms upto the order ϵ^0, we have

$$\gamma^\mu a_0 \left(\frac{-i\partial_\mu \varphi}{\epsilon}\right) e^{-i\varphi/\epsilon} + \gamma^\mu (\nabla_\mu a_0) e^{-i\varphi/\epsilon} + \gamma_\mu a_1 \epsilon \left(\frac{-i\partial_\mu \varphi}{\epsilon}\right) e^{-i\varphi/\epsilon} = 0,$$

$$\gamma^\mu a_0 \left(\frac{-ip_\mu}{\epsilon}\right) + \gamma^\mu (\nabla_\mu a_0) + \gamma^\mu a_1 (-ip_\mu) = 0.$$

At the order of ϵ^{-1} we obtain

$$\gamma^\mu p_\mu a_0 = 0. \tag{12}$$

Let U_L and U_R be respectively the left-handed and right-handed eigenspinor solutions of Eq. (12) with positive energy ($p_0 > 0$). Similarly V_L and V_R be respectively the left- and right-handed anti-particle eignespinors ($p_0 < 0$). Thus we can say that $a_0 = U_\alpha(p) C(x)^\alpha$ where C^α is the complex number and $\alpha \in \{L, R\}$.

At the order ϵ^0

$$\gamma^\mu \nabla_\mu a_0 - i\gamma^\mu p_\mu a_1 = 0. \tag{13}$$

Pre-multiplying Eq. (13) with $\bar{U}_\beta$ where $\beta \in \{L, R\}$ and using $\bar{U}_\beta \gamma^\mu p_\mu = 0$, we obtain

$$\bar{U}_\beta(\gamma^\mu \nabla_\mu a_0) = 0. \tag{14}$$

Similarly, expanding $a_0 = U_\alpha C^\alpha$, we obtain

$$(\bar{U}_\beta \gamma^\mu U_\alpha)\nabla_\mu C^\alpha + (\bar{U}_\beta \gamma^\mu \nabla_\mu U_\alpha) C^\alpha = 0. \tag{15}$$

Now we need to use a relation for the four-current to isolate the Berry connection. However, clearly, simply putting $m = 0$ in the relation that we used in the massive case described in Section 3 would not work because the RHS diverges in Eq. (7). It is possible to derive the relation for the four-current if we use the two-spinor representation for the Eigen spinors. We know that the four-spinors can be written in terms of the two-spinors as

$$U_L = \begin{pmatrix} u_L \\ 0 \end{pmatrix} \text{ and } U_R = \begin{pmatrix} 0 \\ u_R \end{pmatrix}, \tag{16}$$

$$\bar{U}_L = (0, u_L^\dagger) \text{ and } \bar{U}_R = (u_R^\dagger, 0), \tag{17}$$

$$\gamma^\mu = \begin{bmatrix} 0 & \sigma^\mu \\ \bar{\sigma}^\mu & 0 \end{bmatrix}, \tag{18}$$

where $\bar{\sigma}^\mu = (1, -\boldsymbol{\sigma})$ and $\sigma^\mu = (1, \boldsymbol{\sigma})$ and u_α-s are two-spinors. Note that in Eqs. (16) and (17), 0 represents $\begin{pmatrix} 0 \\ 0 \end{pmatrix}$ and similarly in Eq. (18) it represents 2×2 null matrix. Same relations are valid for antiparticle four-spinors V_α and their corresponding two-spinors v_α.

Substituting these relations is Eq. (10) we can derive the relation for the four-current in this case. The details of this calculations can be found elsewhere. We will finally obtain that

$$\bar{U}_\alpha \gamma^\mu U_\beta = -\delta_{\alpha\beta}\frac{p^\mu}{p_0} = -\delta_{\alpha\beta}\frac{p^\mu}{p_\nu e_0^\nu} = \delta_{\alpha\beta} H^\mu, \tag{19}$$

where $\alpha, \beta \in \{L, R\}$. We see that the quantity H^μ is frame-dependent because of the fact it contains e_0^ν, which is different from the massive case. This is because of the fact that for a massless particle, there is no rest frame. This is the reason that the expression that we obtain for the four-current is also observer-dependent. Using Eqs. (19) and (15), it can be shown that

$$(\delta_{\alpha\beta} H^\mu \nabla_\mu + \frac{1}{2}\delta_{\alpha\beta}\nabla_\mu H^\mu + \frac{1}{2} H^\mu(\bar{U}_\alpha \gamma^0 \nabla_\mu U_\beta - \nabla_\mu \bar{U}_\alpha \gamma^0 U_\beta))C^\beta = 0. \tag{20}$$

The details of these calculations can be found elsewhere.

Now similar to the massive case, we can define the Berry connection as

$$B_{\mu\alpha\beta} = \frac{i}{2}(\bar{U}_\alpha \gamma^0 \nabla_\mu U_\beta - \nabla_\mu \bar{U}_\alpha \gamma^0 U_\beta). \tag{21}$$

Here we see that we have extra γ^0 in the expression when compared to the massive case which is due to the fact that we are using Weyl's representation of gamma matrices.

5. Pancharatnam-Berry-like and Aharonov-Bohm-like terms

Now in the massive case we would use Eq. (2) in Eq. (9) to isolate the Pancharatnam-Berry-like and Aharonov-Bohm-like terms. Taking adjoint of Eq. (2) we have

$$\nabla_\mu u_\alpha^\dagger = \partial_\mu u_\alpha^\dagger + u_\alpha^\dagger (\Omega_\mu)^\dagger. \tag{22}$$

It can be shown using Eq. (3) that $(\Omega_\mu)^\dagger = -\gamma_0 \Omega_\mu \gamma_0$. Thus using this and multiplying γ_0 from the right in Eq. (22) we obtain

$$\nabla_\mu \bar{u}_\alpha = \partial_\mu \bar{u}_\alpha - \bar{u}_\alpha \Omega_\mu. \tag{23}$$

Substituting Eqs. (22) and (23) in Eq. (9), we obtain

$$B_{\mu\alpha\beta} = \frac{i}{2}\Big[(\bar{u}_\alpha \partial_\mu u_\beta - \partial_\mu \bar{u}_\alpha u_\beta) + 2(\bar{u}_\alpha \Omega_\mu u_\beta)\Big]. \tag{24}$$

Only the term $2(\bar{u}_\alpha \Omega_\mu u_\beta)$ is due to the spinor connection. The rest of the terms are also present in the case of flat spacetime and correspond to the Berry connection in flat spacetime [1]. Thus we can say

$$B_{\mu\alpha\beta} = B^{flat}_{\mu\alpha\beta} + i(\bar{u}_\alpha \Omega_\mu u_\beta). \tag{25}$$

Now we can split this extra term to seperate the Pancharatnam-Berry-like and Aharonov-Bohm-like terms. We can expand the term

$$\bar{u}_\alpha \Omega_\nu u_\beta = \frac{1}{8}(\omega_{ab\nu})(\bar{u}_\alpha [\gamma^a, \gamma^b] u_\beta), \tag{26}$$

Hence,

$$\bar{u}_\alpha \Omega_\nu u_\beta = \frac{1}{8}(\omega_{0b\nu}\bar{u}_\alpha [\gamma^0, \gamma^b] u_\beta + \omega_{a0\nu}\bar{u}_\alpha [\gamma^a, \gamma^0] u_\beta + \bar{u}_\alpha \omega_{ij\nu}[\gamma^i, \gamma^j] u_\beta), \tag{27}$$

where $i, j \in \{1, 2, 3\}$, which can be simplified as

$$\bar{u}_\alpha \Omega_\nu u_\beta = \frac{1}{8}((\omega_{0i\nu} - \omega_{i0\nu})\bar{u}_\alpha [\gamma^0, \gamma^i] u_\beta) + \frac{1}{8}\omega_{ij\nu}\bar{u}_\alpha [\gamma^i, \gamma^j] u_\beta. \tag{28}$$

Now the second term of R.H.S. vanishes when the metric is spherically symmetric. If the metric is spherically symmetric then $\omega_{ij\nu}$ is non zero only when $i = j$ but then $[\gamma^i, \gamma^j] = 0$ thus making the term $\frac{1}{8}\omega_{ij\nu}\bar{u}_\alpha [\gamma^i, \gamma^j] u_\beta = 0$. Therefore, we can define the first and second terms as Pancharatnam-Berry-like and Aharonov-Bohm-like respectively. Thus we have

$$B_{\mu\alpha\beta} = B^{flat}_{\mu\alpha\beta} + \frac{i}{8}((\omega_{0i\nu} - \omega_{i0\nu})\bar{u}_\alpha [\gamma^0, \gamma^i] u_\beta) + \frac{i}{8}\omega_{ij\nu}\bar{u}_\alpha [\gamma^i, \gamma^j] u_\beta. \tag{29}$$

6. Conclusion

We have found the covariant description of Berry connection for spin half particles. The connection that we have derived is in the absence of an electromagnetic field. The same calculations can be repeated considering the electromagnetic field as well, and we would get a similar result, but the final expression would contain additional terms with $F_{\mu\nu}$. These calculations can be found elsewhere. We have found a similar expression for the Berry connection in the massless case. However, the connection there is an observer-dependent quantity, unlike the massive case. This can be attributed to the fact that there is no rest frame for a massless particle. Finally, we have found that it is possible to isolate the Pancharatnam-Berry-like and Aharonov-Bohm-like terms from the Berry connection. The last result was also observed in the $3 + 1$ formalism of the geometric phase [2, 3, 4].

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Scientific Voyage
Vol. 3, No. 1,
Page 25-31 (2022)

SCIENTIFIC VOYAGE
ISSN: 2395-5546

GCECT
Publication
Jan - Mar

A note on the modified Newtonian gravity and its application

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Abstract: In the present work we propose to modify the Newtonian gravitational law by incorporating a velocity dependence term which can be augmented with the Hubble's law. We have applied the modified formula to local galactic systems to account for the recessional velocity of the galaxies and hence expanding phase of the universe. The model seems physically viable on the theoretical ground, however its future feasibility in connection to several other astrophysical observations is to be sought for.

Keywords: Newtonian gravitational law; Hubble's law; galactic systems; recessional velocity

1. Introduction

To understand the mechanism behind the motions of the planets, stars, nebulae and hence as a whole the so-called universe in the ancient time as was usually viewed by people was a challenge to the philosophers for several millenniums starting from Maya to Greek civilizations. The genuine research to unfold the mysteries of the heavenly bodies started in the medieval period when Copernicus (1473 - 1543), Brahe (1546 - 1601) and Kepler (1571 - 1630) considered the issue with scientific temperament via theory as well as observation [1]. Eventually Newton (1642 - 1726) conceived the background idea and generalized the Keplerian laws of planetary motion into a unique Law of Gravitation which is the first great unification in science [2].

This law has been received tremendous success throughout the last few centuries which reads as

$$F_N = -\frac{Gm_1m_2}{r^2}, \tag{1}$$

where F_N is the attractive force acting between two bodies of masses m_1 and m_2 at a distance r and G is the universal gravitational constant.

However, time and again discrepancies also have been pointed out by several scientists. It is stated by Ghosh and Dey [3] that in the 19th century, when mathematical tools became more matured, some serious problems were faced with this law where a number of manifestations of the paradox leading to inconsistent results, infinite potential, etc. Historically, the first modification in the law was suggested by Laplace [4] where the gravitational constant G was assumed to be exponentially varying with distance as follows:

$$F_{mod} = -F_N exp(-\Gamma r), \tag{2}$$

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where Γ denotes the intensity of attenuation of gravity.

Long back, one century ago, See [5] assumed the changes in the Newtonian law of gravitation as indicated by the various latest researches on the motions of planets and the moon to account for the Mercury's perihelion motion and other astronomical phenomena. He basically employed the formula provided by Weber [6] which is as follows:

$$F_{mod} = F_N \left[1 - \frac{1}{c^2}\left(\frac{dr}{dt}\right)^2 + \frac{2r}{c^2}\left(\frac{d^2r}{dt^2}\right)\right]. \tag{3}$$

As can be noticed, the above Eq. (3) has one small second term depending on $(dr/dt)^2$ which represents square of the velocity in the direction of the radius vector and another small third term depending on d^2r/dt^2, which is the acceleration, i.e. change of the velocity in the direction of the radius vector. This modified formula accounts for the Mercury's perihelion motion and other astronomical phenomena. However, in the present investigation we confine ourselves within the periphery of purely classical gravitation of Newton and are not considering the gravitation of Einstein, known as General Relativity, which accurately explains the Mercury's perihelion motion and acts fantastically for massive celestial bodies, e.g. compact stars, galaxies and so on.

Another modification of Newton's laws to account for observed properties of galaxies was put forward by Milgrom [7], known as the Modified Newtonian Dynamics (MOND), where the special form of the formula has been proposed as

$$F_{mod} = m_1 \mu\left(\frac{a^2}{a_0}\right), \tag{4}$$

where m_1 is the object's gravitational mass, a is its acceleration, $\mu(x)$ is the interpolating function and a_0 is a new fundamental constant which marks the transition between the Newtonian and deep-MOND regimes.

In recent years many scientists have suggested different modifications of the gravitational law. It has been shown by Whitehouse and Kraniotis [8] that the flat rotation curve of galaxies may be explained by the cosmological term Λ and presence of dark matter is not necessary if Newtons gravitational equation is modified in the form

$$F_{mod} = -F_N + G_\Lambda m_2 r, \tag{5}$$

where G_Λ is the gravitational force exerted by the cosmological term Λ and represents a fifth fundamental force which is directly proportional to the distance.

On the other hand, Kirillov and Turaev [9] by using a Modified Field Theory (MOFT) have shown that the renormalization of the gravitational constant leads to the deviation of the law of gravity from the Newtons law in which the gravitational potential shows essentially logarithmic, i.e. $ln\ r$ (instead of $1/r$) behavior and hence the renormalized value of the gravitational constant G varies as increasing manner (in this connection for a detailed review on Dirac's Large Number Hypothesis (LNH) vide [10]). Based on the suggestion that the gravity is originally an entropic force a modified Newton's law of gravitation has been acheived by Ali and Towfik [11]. They argue that the modification agrees with different sign with the prediction of Randall-Sundrum II model which contains one uncompactified extra dimension and such modification may have observable consequences at length scales much

larger than the Planck scale.

2. A simple modification of Newton's law of gravity

Currently our universe is expanding [12] with acceleration [13,14]. As a result, all the celestial bodies, especially the galaxies are moving away from each other. Equivalently, all the galaxies are moving away from our Galaxy, i.e. Milky Way and hence from the Earth. The Newtonian Law of Gravitation [2] works fine in our Solar system and even in short/middle distance but fails at a cosmological distance which is of the order of Megaparsec (Mpc).

Thus there is a need to modify the gravitational law to resolve this problem. However, our proposal is not completely *ad hoc* rather we are keeping in mind the expanding universe [12] and therefore propose for a modified formula which represents more general form of Newton's law of gravity and can be expressed as

$$F_{mod} = -F_N + F_N\dot{r}, \tag{6}$$

where $v = \dot{r}$ is the universal velocity.

In the above Eq. (6) we have considered that the Newtonian force acts as inverse square form of distance as well as directly proportional to velocity and can be rewritten as

$$F_{mod} = -F_N(1 - \dot{r}). \tag{7}$$

It is interesting to note that the second term in our Eq. (7) resembles with the square of the velocity term acting in the direction of the radius vector as proposed by Weber [6,5,15]. One can also note that Ghosh [16] has proposed model of Inertial Induction (as coined by Sciama [17] for the acceleration-dependent extra term) based upon an extension of Mach's Principle according to which the gravitational interaction between two masses depends not only on their distance but also on their relative velocity. It is curious that in this extended gravitational model the force law comes out as $F = ma+$ a small drag term. By using this model Ghosh [16] could quantitatively explain the cosmological redshift in a quasi-static infinite universe. Interestingly, the theory of Inertial Induction also provides feasible results regarding the dynamic gravitation phenomenon of the Earth on its satellites as a possible partial cause for orbital decay [18]. In connection to Inertial Induction it may be pointed out that not only the redshift and satellite orbit decay rather quite a few phenomena got explained by Ghosh and collaborators [19,20,21,22,23].

Now assuming that the above velocity involves in the Hubble law, i.e. $H = \dot{r}/r$, we can modify Eq. (7) as follows

$$F_{mod} = -\frac{Gm_1m_2}{r^2}(1 - Hr), \tag{8}$$

where H is the Hubble constant.

Now acceleration can be, from Eq. (8), defined by the Gravitational force on unit mass of Galaxy due to Earth as follows

$$a = \frac{F_{mod}}{m_1} = -\frac{Gm_2}{r^2}(1 - Hr). \tag{9}$$

The Newtonian Law [Eq. (1)] works fine when distance is less than 0.1 Mpc (it is to note that the average distance between galaxies is 1 to 10 Mpc). However,

beyond the distance $r > 0.1$ Mpc, the gravitational pull becomes ineffective and as a result the galaxies keep moving away from each other.

3. Application of the modified law: A few test cases

3.1 The Earth-Moon system

Let us consider the following data set: $G = 6.674 \times 10^{-11}\ m^3/kg/s^{-2}$ and $1\ Mpc = 3.08 \times 10^{22}$ m, the mass of the Earth $m_1 = 6 \times 10^{24}$ kg, the mass of the Moon $m_2 = 7.342 \times 10^{22}$ kg, average distance between the Earth-Moon system $r = 3.84 \times 10^8$ m [24].

Putting these values in Eq. (8), in order to verify it, we can get the gravitational force working in between two celestial bodies. So, for the Earth and Moon system, according to the new formula we can have

$$F_{mod} = -19.83 \times 10^{19}(1 - 8.96 \times 10^{-13}) \text{ dynes.} \tag{10}$$

The second term inside the bracket is much less than the first term and so the gravitational force is negative showing the nature of it as the force of attraction. Hence as far as the above data is concerned the modified formula works fine in this case.

3.2 The Earth-Sun system

Putting the values of mass of the Sun $m_2 = 2 \times 10^{30}$ kg, distance between the Earth and Sun $R = 1.5 \times 10^{11}$ m in Eq. (8), we get the gravitational force between the Sun and Earth as

$$F_{mod} = -360 \times 10^{20}(1 - 3.5 \times 10^{-10}) \text{ dynes.} \tag{11}$$

The negative sign in Eq. (11) indicates that the resultant force is attractive between the Sun and Earth.

3.3 The Saturn-Sun system

Taking mass of the Saturn $m_1 = 5.683 \times 10^{26}$ kg, mass of the Sun $m_2 = 2 \times 10^{30}$ kg, distance between the Earth and Sun $R = 1.433 \times 10^{12}$ m, we get from Eq. (8), the gravitational force between Sun and Saturn as

$$F_{mod} = -37.9 \times 10^{21}(1 - 3.34 \times 10^{-9}) \text{ dynes.} \tag{12}$$

Here also the resultant force is attractive in nature between the Sun and Saturn.

3.4 The Earth-Virgo system

We consider her the data set as follows: mass of the Virgo $m_1 = 2.4 \times 10^{45}$ kg, distance of the Virgo from the Earth $R = 17.14$ Mpc$= 5.14 \times 10^{23}$ m. These values from Eq. (8) provide the gravitational force between Earth and Virgo as

$$F_{mod} = -3.6 \times 10^{12}(1 - 1200) \text{ dynes.} \tag{13}$$

Here the first term within bracket is very small compared to the second term. So the gravitational force between the Earth and Virgo is negative and hence repulsive in nature. Therefore the galaxy is moving away from the Earth.

The acceleration of this galaxy can be determined by using Eq. (9) as follows:

$$a = 1.5 \times 10^{-33} \times (1 - 1200)\ km/s^2. \tag{14}$$

On the other hand, according to the original Newtonian Law the acceleration of the galaxy is

$$a = 1.5 \times 10^{-33}\ km/s^2. \tag{15}$$

So, according to the new formula we can see acceleration of this galaxy is faster than that derived from the old formula by a factor (1-1200) $\approx$ -1200. Interestingly, the numerical value of this factor is nearly the same as the recessional velocity (v) of this galaxy where $v = Hr$, where H is the Hubbles constant as mentioned earlier.

3.5 The Earth-Corona Borealis system

The mass of Corona Borealis $m_1 = 24 \times 10^{46}$ kg, mass of the Earth $m_2 = 6 \times 10^{24}$ kg, distance of the Corona Borealis from Earth $r = 314.28Mpc = 314.28 \times 3 \times 10^{22}$ m. Putting these values in Eq. (8), we get the gravitational force between the Earth and Virgo as

$$F_{mod} = -1.09 \times 10^{12}(1 - 22000)\ \text{dynes}. \tag{16}$$

Here the first term within the bracket is very small compared to the second term. So the gravitational force between the Earth and Corona Borealis is positive and being repulsive the galaxy is moving away from the Earth. Likewise the previous case, it is to verify that according to this formula the acceleration of the galaxy becomes faster than that derived from the original Newtonian formula by a factor (1 - 22000) $\approx$ - 22000 which numerically is exactly the same as the recessional velocity (v) of the galaxy under consideration.

In a similar way, one can go on to find out the gravitational force between the Earth and any other galaxy according to the modified formula. In Table 1 a list of some important galaxies with the redshift and their distance from the Earth are provided by taking the value of the Hubble constant as 70 $km/s/Mpc$ [25, 26, 27] which is the accepted value at present day. However, for the observed redshift we have used data from the book by Schneider [24] where the value of the Hubble constant was available from the old source as $H = 80\ km/s/Mpc$.

Table 1 Estimated redshift from the proposed model for $H = 70$ km/s/Mpc [25, 26, 27]

Galaxy	**Observed distance** (in Mpc)	**Observed redshift** (in km/sec)	**Estimated redshift** (in km/sec)
Virgo	17.14	1,200	1,199
Ursa Major	220	15,400	15,399
Corona Borealis	314.28	22,000	21,999
Bootes	562.85	39,400	39,399
Hydra	865.71	60,600	60,599

4. Conclusion

In this study we have presented a simple phenomenological model and modified the Newtonian gravitational law to account for the recessional velocity of galaxies.

To verify the proposed formula we have applied it arbitrarily to five galaxies and the data are included in Table 1. The results as shown in this table indicate that when the distance between two celestial objects is more than 1 Mpc the estimated redshift from our proposed modified formula fits remarkably with the observed values and this therefore admits the feasibility of our phenomenological model. To explain the expanding universe it can be argued that, as a consequence of this new law acting at a Mpc distance scale, the gravitational pull between them gradually becomes very weak and they keep increasing the recessional velocities.

Although there are striking resemblances between the observed and estimated values of the redshift for a set of galaxies, however issues are also involved in the theoretical as well as the applied fields which may be listed as follows: (i) how far the modified formula could account for the accelerating phase of the universe [13, 14], (ii) in the modified formula only the velocity term along with the distance has been considered to adapt with the expanding universe, however, following the works of Weber [6], See [5], Milgrom [7] and Ghosh [16] one can also logically approach to add the acceleration term in the formula to look for further features and (iii) specifically how the Milgrom law [Eq. (4)] due to MOND theory [7] and the allied astrophysical as well as cosmological issues can be addressed from the viewpoint of the modified Newtonian law presented in this paper. All these issues can be taken into account in future projects.

Acknowledgment

SR is grateful to the authority of the Inter-University Centre for Astronomy and Astrophysics (IUCAA), Pune, India for providing Visiting Associateship under which a part of this work was carried out.

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Scientific Voyage
Vol. 3, No. 1,
Page 32-38 (2022)

SCIENTIFIC VOYAGE
ISSN: 2395-5546

GCECT
Publication
Jan - Mar

BOOK REVIEW

Suman Beri - Higgs Boson, Top Quark and Single Top Quark
The Story of a Punjabi Woman Scientist

Rajinder Singh

Shaker Verlag, Düren, Germany/**2022**

Price: 23.90 Euro; Pages: xxiv +160

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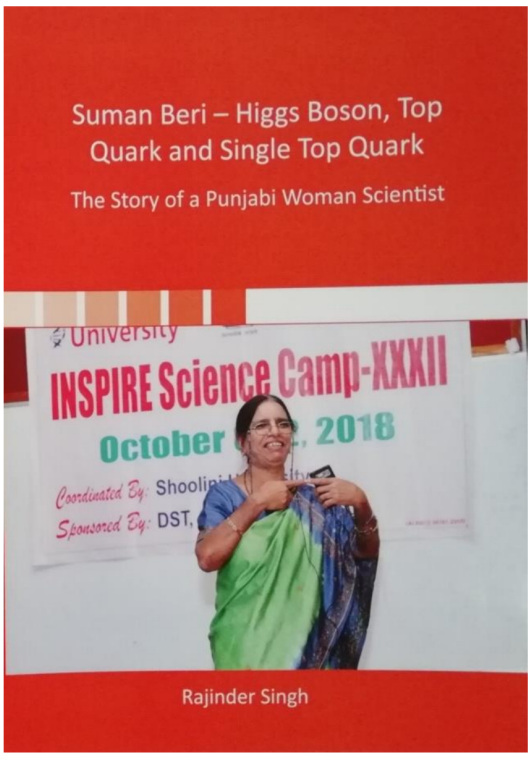

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In the **Preface**, Rajinder Singh, the author of this volume, recounts his achievements in the history of Indian Science. I felt humbled by his track record of 100 research publications and 39 books in this domain. So this volume is 40th in the series. He also recounts the reasons for undertaking this onerous task: "In 2021, on the Women Science Day, in Chandigarh, the Society for the Promotion of Science and Technology of India invited prominent female scientists from different fields of research, to deliver lectures. Professor Suman Bala Beri, formerly at the Punjab University (PU) Chandigarh, was one of them. I was fascinated by her life story, as she is the first female Professor of the Physics Department, PU. In addition to that, she is one of the first female Indian scientists to work on high energy particle physics". He acknowledges the help of Prof. Arun Kumar Grover, Ex-VC PU, for providing moral support and help.

The Foreword to this volume is written by Prof. Bindu Bambah, Ex-Senior Professor of University of Hyderabad, and herself a prominent Theoretical Particle Physicist. Bindu writes: "I have known her for nearly 50 years, half a century of ups and downs. How can one write objectively about a person one has known since childhood, as a teacher, friend and physicist? So, if my words sound subjective, it is with a reason. There is emotion involved, and with feeling invariably comes subjectivity". Bindu ends her write up by paying glowing tributes to Suman: "This book is a biography of one such a "Violet", and I hope it spreads the fragrance of her life as a role model for coming generations of women. Let them be inspired by a life in Physics that overcame many hurdles, many downfalls, and many losses but still survived to be part of not only the top quark discovery but the Higgs search as well".

In his message, Prof. Arun Kumar Grover, Ex-VC of PU Chandigarh, narrates how he motivated Rajinder Singh to write biographies of BM Anand and Suman Beri: "In March 2021, he proposed to write a biography of Suman Beri and I offered to assist him in collation of relevant material available in PU and TIFR and also put him in contact with scientists who have known her".

In the **Introduction** to this volume, author writes: "Suman Beri is one of the inventors of top quark, single top quark and Higgs boson. She is one of the top ten Indian physicists with highest h-index. She is honoured by different institutions. She is one of the persons who work for the promotion of girls' education. To the best of my knowledge, there is no book which deals with her life and science. The present book intends to fill the gap".

Chapter 1 deals with family life of Suman Beri. She belongs to a middle class family of Himachal area of old Punjab but her father was Headmaster of a High School in Simla. All her siblings got good education. Her parents played important role in molding the direction of her life as a prominent future scientist. She had interest in Physics, Chemistry and Mathematics. However, Physics was her favorite subject.

The story of her admission to PU Honours School in Physics is interesting. The day she entered the Physics block, some senior Professor entreated her with the query: "Physics is a tough subject – have you thought about it". She was not discouraged by his remark. She got admission to B.Sc. (Honours School) and passed BSc (Honour School) in 1969, and MSc (Honour School) in 1970 from the Punjab University, both in the first division. Suman was motivated by KL Verma, an old student of her father, to join as Research Scholar in the department.

Suman was encouraged by her parents to choose research as a career. She was married in 1977 but unfortunately her husband died in 1992 and her dreams were shattered. But Suman found solace in moving on in life by engaging full time in research. She recounts: "*There were two options - either I absorb myself fully to work not giving any time to my mind for anything else OR do not do anything and wait for life to finish without any contribution. Here I chose first option.*"

Chapter 2 deals with views of Suman's colleagues, students, friends and relatives. This is the lengthiest Chapter covering more than 50 pages. Her well wishers include Gurmukh Singh and Manjit Kaur, her research collaborators in PU, Keya Dharamvir, Bindu Bambah & RK Puri of PU Physics, RK Kohli, DUI PU; her foreign collaborators, Ph.D. Scholars supervised by Suman, and her friends and relatives. I found the views of Harrison Prosper, her research collaborator in D0 experiment, as the best tribute to Suman: "I found Suman to be very approachable and quickly learned that this pleasant highly inquisitive physicist demanded clarity and precision in our discussions of scientific matters. Later, when she embarked on a long, distinguished, career as a gifted mentor of young people, I would learn of other important traits: the highly inquisitive physicist was also kind, thoughtful, and firm; she holds herself and her students to high standards, and she insists that projects started be brought to satisfactory conclusions. *Professor Beri has left her mark on the scientific enterprise of India not only through her*

scientific contributions but also through the many young people who have had the good fortune of having been mentored by Suman Beri"

Chapter 3 is one of the core Chapters based on the Doctoral Thesis of Suman Beri. The author traces the roots of cosmic ray research in Punjab. "*The cosmic ray research began in Lahore due to a visit by the American scientist Arthur H. Compton in 1926.* As Punjab University did not possess its own laboratories, the main research work was done at the Government College Lahore and Christian Forman College".

Suman Bala wrote her thesis on "*A comparative study of the fluxes of low energy helium and Z ≥ 10 nuclei in primary cosmic rays over Fort Churchill in 1963, 1964 and 1967*". What motivated her to begin this research? Suman wrote that it was a paper by T.F. Cleghorn *et al.* on "The effects of solar modulation on the energy spectrum of heavy cosmic ray nuclei". She pointed out the following two drawbacks in their results: (i) "low statistics", and (ii) the helium and Z ≥ 10 nuclei fluxes were taken from experiments, performed at different times.

In her thesis, Suman studied: (i) Relative modulation of helium and Z ≥ 10 (nuclei with 10≤Z≤28). (ii) "Characteristics of interstellar propagation of these nuclei". After applying different corrections (scanning loss, loss due to interaction in the stack, correction for Z≥ 10 nuclei, correction for solid angle, 'correction for loss due to air-cut-off', 'correction due to fragmentations and ionisation losses in air'), she determined the differential energy fluxes on the top of the earth's atmosphere for helium and heavy nuclei. She was awarded her Ph.D. degree in March. 1976.

Chapter 4 gives details of her teaching career in PU Chandigarh. Suman joined as Teaching Assistant in 1974 and re-designated as Lecturer in 1981. Her duties included teaching Theory and Practical courses, supervising M.Phil. dissertations and doing research work on Cosmic rays. In due course of time, she was promoted as Reader in 1987 and as Professor in 2001. Her application for Professorship shows her achievements in research and participation in research projects as Co- or Principal Investigator, and collaborator in major International projects like D0 and CMS experiments at Fermi Lab. and CERN, respectively. This Chapter gives details of Ph.D. theses guided by Suman: 9 under CMS Project and 5 under D-Zero collaboration.

Chapter 5 describes Suman's international connections and important scientific discoveries. Her scientific work deals with the detection of cosmic rays and fundamental particles of the standard model. The author gives description of some old techniquxes of particle detection and new detectors being used at CERN and Fermi Lab. This Chapter also narrates the trials and tribulations of Suman Beri to get duty leave, travel grants and other facilities to participate in international projects abroad. It shows her "*perseverance, grit and patience*" to overcome the bureaucratic hurdles created by the university administration. I wonder she not only survived but also won laurels by her success stories in the international projects.

The author gives details of discoveries made by Suman in this Chapter. She was a participant in discovery of "*top quark*", "*single top quark*" and "*Higgs Boson*". The mass of top quark and its production cross-section was determined at the Fermi Lab. Tevatron. How difficult is to discover these elementary particles of the Standard Model will be clear from this statement: "*Searching for single-top production makes finding a needle in a haystack look easy. Only one in every 20 billion proton-antiproton collisions produces a single top quark. Even worse, the signal of these rare occurrences is easily mimicked by other "background" processes that occur at much higher rates.*"

Chapter 6 gives details of Suman's media interactions. Generally, Indian media ignores the scientific achievements of Scientists and keep busy reporting of political and sports events which are liked by the public. However, Suman got lot of media attention in Chandigarh after the discovery of single top quark and Higgs Boson. A local newspaper reported on March 12, 2009: "*In the discovery of the single top quark, Suman Beri played leading role. The team headed by Prof. Suman Beri also collaborated in the D-Zero experiment.*"

The recent trend to boast of the contribution of a scientist is the h-index, which measures the productivity and citation impact of the publications. Not only due to her scientific achievements, but also for the importance of her publications on the international and national level, local media reported on her. *She is among the TOP TEN highly cited scientists of India and occupies the Top position in PU list of achievers.*

Chapter 7 mentions Suman's achievements through Awards and Honours bestowed upon her. As mentioned in the last two Chapters, Suman came into limelight due to her participation in discoveries of 3 new particles. She was honoured by the University Syndicate "*for actively participating in the exciting discovery of top quark and as co-author of top discovery paper which had citation of more than 800 (D0 collaboration, Fermi Lab, USA)*". Suman Beri was awarded CSIR Emeritus Scientist status in 2012, and UGC Emeritus Fellowship from 2015-2017. She is the first female Professor to be honoured as 'Professor emeritus' in the department of physics.

In **Chapter 8** "Concluding Remarks", the author sums up his impressions about Suman Beri, her achievements in life, and the Indian University system:

1. Suman Bala Beri's life is an encouraging story for younger generation, in particular girls/boys from the middle class. She inspired many and touched the lives of those, with whom she came in contact.
2. Author takes a dig at Indian Science Academies: "In spite of SB's or Manjit Kaur's high h-index and huge number of publications, they are not elected as Fellows of any of the three academies. Why so"?
3. Success has its own price. We have seen that she has to often beg the authorities for duty leaves. She often worked on half-pay or without pay, while she was abroad.
4. Author appreciates Suman's life philosophy: "I personally differentiate between religion and science. They are two opposite poles. They have nothing to do with each other. Still, I believe that Suman Beri's biography is of interest, because her religious life philosophy is to help mankind; and apply her religious idea to motivate students to do good science research".

There is an Appendix listing Suman's 32 research publications during 1971-1985. Of course, she has more than 1600 publications in all, most of these under her collaborative research projects. As usual, Rajinder Singh gives an exhaustive list of bibliography at the end of the volume.

I may point out some mistakes which crept in due to oversight or error of judgement. For example, in Gurmukh Singh's narrative (p. 18), PU Chandigarh is being confused with Chandigarh University without realizing that there is a private

University of this name located at Gharuan, near Kharar. Forman Christian College is being written as Christian Forman College (p. 65). Piara Singh Gill (p. 66) was never a student of Forman Christian College, he was a teacher there. There are some typos which need to be taken into account in the next edition.

I enjoyed reading this biography as there is lot of new information about Suman Beri which I relish. I know her since the last 50 years and met her just after my return from Marie Curie University, Paris. This is an inspiring biography for our young students, specially the girls of this country who face lot of hardships in the patriarchal society of India. Suman is a role model for our girl students.

Scientific Voyage
Vol. 3, No. 1,
Page 39-49 (2022)

SCIENTIFIC VOYAGE
ISSN: 2395-5546

GCECT
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European Astronomical Society
2022 Prizes

Tycho Brahe Medal

The 2022 Tycho Brahe Medal is awarded to **Dr Jean-Luc Starck (CEA Paris Saclay, France)** *for the development of novel astro-statistics methods and open source analysis tools which have enabled optimal scientific exploitation of astronomical data obtained from European space and ground based facilities leading to major discoveries in extragalactic astrophysics and cosmology.*

Lodewijk Woltjer Lecture

The 2022 Lodewijk Woltjer Lecture is awarded to **Prof. Bożena Czerny (Center for Theoretical Physics, Polish Academy of Sciences, Poland)** *for her contributions to our understanding of the physics of accretion disks and the broad line regions in active galactic nuclei, as well as for her application of quasars to constrain the cosmological model at high redshift and open a window on the role of dark energy.*

Fritz Zwicky Prize for Astrophysics & Cosmology

The 2022 Fritz Zwicky Prize for Astrophysics & Cosmology is awarded to **Prof. Ewine F. van Dishoeck (Leiden University, the Netherlands)** *for her groundbreaking, decades-spanning, work in observational astrochemistry and molecular spectroscopy, revealing the secrets of molecules from interstellar clouds to star and planet formation, and for her leadership within the astronomical community.*

MERAC Prizes

The 2022 MERAC Prizes for the Best PhD Thesis are awarded in

Theoretical Astrophysics

to **Dr Helmer Koppelman (the Netherlands)** *for his multi-faceted approach to the field of galactic archaeology that transformed our understanding of the history and dynamics of the Milky Way.*

Observational Astrophysics

to **Dr Núria Miret Roig (University of Vienna, Austria)** *for the discovery of many new free-floating planets, which illuminated the origin of these exotic nomad planets.*

New Technologies (Instrumental)

to **Dr Ewelina Obrzud (Centre Suisse d'Electronique et de Microtechnique, Switzerland)** *for the development of novel laser frequency combs for the accurate calibration and extreme radial velocity-precision of astronomical spectrographs.*

All six awardees will give a plenary lecture at the European Astronomical Society Annual Meeting 2022 to be held in Valencia, Spain, from 27 June to 1 July 2022.

The European Astronomical Society (EAS) promotes and advances astronomy in Europe. As an independent body, the EAS can act on matters that need to be handled at a European level on behalf of the European astronomical community.

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The Tycho Brahe Medal is awarded in recognition of the development or exploitation of European instruments or major discoveries based largely on such instruments.

Tycho Brahe Medal

The 2022 Tycho Brahe Medal is awarded to **Dr Jean-Luc Starck (CEA Paris Saclay, France)** *for the development of novel astro-statistics methods and open source analysis tools which have enabled optimal scientific exploitation of astronomical data obtained from European space and ground based facilities leading to major discoveries in extragalactic astrophysics and cosmology.*

Dr Jean-Luc Starck is Director of Research at CEA Saclay, France. He holds a Ph.D from Nice Observatory (1992) and a Habilitation from the University Paris XI. In 2010 he founded and has since been leading the CosmoStat lab at CEA, an interdisciplinary research group performing cutting edge research at the interface between astrophysics, cosmology and statistics. Dr. Starck served as the first vice-president of the International Astrostatistics Association (2012-2018) and received the IAA fellowship in 2016. He has received the EADS prize of the French Academy of Science in 2011, as well as the 2018 Gruber Prize in Cosmology (as a member of the ESA Planck team) and is member of Academia Europae (since 2021). Over the last 10 years, he has been awarded competitive research funding including an Advanced ERC. He has published over 250 refereed papers in astrophysics, cosmology, signal processing and applied mathematics, which have received more than 89,000 citations and he is also author of three books. He is heavily involved in the Euclid space mission of ESA, which will soon be launched.

Jean-Luc Starck is a pioneer in the field of astrostatistics: Modern telescope facilities produce large amounts of data and require advanced analysis techniques to achieve their scientific goals. Thus astrophysicists have been increasingly relying on statisticians to develop sophisticated and mathematically robust methods to reduce and interpret their data, leading to a new interdisciplinary field, astrostatistics. Dr. Starck is among a handful of scientists leading this dynamic new field. His CEA group has been at the forefront of advancing astrostatistics, providing sophisticated methods and software tools to tackle Big Data management and analysis.

Dr Starck has been a pioneer in the field of harmonic analysis developing new wavelet and curvelet decompositions, and showing how they could be used to solve very ill posed inverse problems, covering a broad range of fields such as sources detection, deconvolution, interferometric image reconstruction, component separation, inpainting and weak lensing mass map recovery. His group has been the first to investigate the concept of compressed sensing in the astrophysical field, leading to the striking results that interferometry radio-image resolution can be improved by 4 using compressed sensing.

His work had a direct impact on the science results of several space projects: the Infrared Space Observatory (ISO) relied on his calibration approach and galaxy detection methods to analyse the first deep infrared surveys opening a new window on dust obscured galaxy evolution at high-z. His work on wavelets and Poisson noise allowed him to propose a solution for deriving robustly both the XMM cluster catalog and the Fermi source catalog. His Morphological Component Analysis method further enabled the study of molecular cloud filaments in star formation. Dr Starck's work on weak lensing had success with HST and will bear strong impact in the future with the Euclid mission.

Dr Starck has put substantial effort for the advancement of astrostatistics via the training of the next generation of scientists. He has supervised more than 30 PhD students and postdocs and he organized 24 astrostatistics conferences and 3 summer schools. He has also published three books in the field of signal processing and astrophysical data analysis geared towards advanced undergraduate and graduate students as well as researchers entering the field.

All these achievements make Dr Jean-Luc Starck an outstanding awardee of the Tycho Brahe Medal.

The Lodewijk Woltjer Lecture honours astronomers of outstanding scientific distinction.

Lodewijk Woltjer Lecture

The 2022 Lodewijk Woltjer Lecture is awarded to **Prof. Bożena Czerny (Center for Theoretical Physics, Polish Academy of Sciences, Poland)** *for her contributions to our understanding of the physics of accretion disks and the broad line regions in active galactic nuclei, as well as for her application of quasars to constrain the cosmological model at high redshift and open a window on the role of dark energy.*

Prof. Bożena Czerny (born Muchotrzeb) studied theoretical physics at Warsaw University, where she obtained her MSc degree in 1974. In 1978 she started working as a research assistant at the Nicolaus Copernicus Astronomical Center of the Polish Academy of Sciences (CAMK), Warsaw, Poland in the field of accretion and obtained her PhD in 1984. Prof Czerny was gradually promoted at CAMK and eventually reached full professor position in 1996. In 2015 she moved to a full time professor position at the Center for Theoretical Physics, Polish Academy of Sciences, Warsaw, Poland, keeping a part-time employment at CAMK till the end of 2017. Prof. Czerny has seved in several committees, such as International Union of Pure and Applied Physics, Council of the National Science Center, and Polish Astronomical Society (President in 2011-2013). She served as a Scientific Editor of the American Astronomical Society journals from 2012 to 2020. She further was awarded in 2019 the Ernst Mach Honorary Medal for Merit in the Physical Sciences awarded by the Czech Academy of Sciences.

Prof. Czerny focuses on modelling the physical processes close to black holes in the centers of active galaxies and in stellar binary systems, and on comparison of the models to the observational data. Her early works started with the understanding of the matter inflow from the inner edge of the disk toward the black hole horizon, which culminated in the contribution to formulation of the slim disk theory. She was among the pioneers in studies of the X-ray variability of active galactic nuclei and of the vertical stratification of the accretion disks, including the idea of the disk warm corona, collaborating with Leicester, Cambridge and Harvard colleagues while working on the emission from accretion disks in AGN. She studied the accretion disk instabilities, comparing their consequences to the observational data. In 2011 she formulated a new model of the Broad Line Region structure in active galactic

nuclei, based on the radiation pressure acting on dust, called FRADO (Failed Radiatively Accelerated Dusty Outflow) model. Recently, she has focused her attention to the application of the light echo measurements of distant quasars to determine the distance to these sources and to derive constraints on the cosmological parameters.

Prof. Czerny was a long-time scientific editor of The Astrophysical Journal published by the American Astronomical Society. Her lecturing and publishing activities include the popularization of astronomy and science in general. Her expertise in research led her to win numerous grants. She is currently PI of a 5-year Maestro grant awarded by the Polish National Science Centre, and since Autumn 2021 she is one of the four PIs of an ERC Synergy Grant aimed to use multi-probe methods to establish the distance scale in the Universe with unprecedented accuracy, which includes also the quasar-based constraints.

The Fritz Zwicky Prize for Astrophysics & Cosmology honours scientists who have obtained fundamental and outstanding results related to astrophysics and/or cosmology. The Fritz Zwicky Prize is awarded biennially, for the first time in 2020, by the European Astronomical Society on behalf of the Fritz Zwicky Foundation, located in Glarus, Switzerland.

The 2022 Fritz Zwicky Prize for Astrophysics & Cosmology is awarded to **Prof. Ewine F. van Dishoeck (Leiden University, the Netherlands)** *for her groundbreaking, decades-spanning, work in observational astrochemistry and molecular spectroscopy, revealing the secrets of molecules from interstellar clouds to star and planet formation, and for her leadership within the astronomical community.*

Fritz Zwicky Prize for Astrophysics & Cosmology

Professor Ewine van Dishoeck is Professor of molecular astrophysics at Leiden University, the Netherlands and external scientific member of the Max Planck Institute for Extraterrestrial Physics. After a MSc in theoretical quantum chemistry; she obtained her PhD in astrochemistry in 1984 from the Leiden University, and held positions at Harvard, Princeton and Caltech before returning to Leiden in 1990. From 2007-2021, she was the scientific director of the Netherlands Research School for Astronomy (NOVA), and since 2009, she is co-Editor of Annual Reviews of Astronomy and Astrophysics. From 2018-2021, van Dishoeck served as the President of the International Astronomical Union (IAU). She has received several prestigious awards, including the 2000 Dutch Spinoza Prize, the 2015 Albert Einstein World Award of Science, the 2018 Kavli Prize for Astrophysics and two ERC Advanced grants. She is a Member or Foreign Associate of several academies, including that of the Netherlands, USA, Germany and Norway.

Prof. van Dishoeck has devoted her career to understanding how these molecules shape the Universe around us. With her unique and comprehensive approach encompassing quantum chemical calculations, laboratory studies, and astronomical modelling and observations, she has pioneered and led the field of astrochemistry and revolutionized our understanding of the physical processes leading to the formation of stars and planets by studying the trail of molecules from star-forming clouds to protoplanetary disks.

A big mystery in the early days of astrochemistry was how large molecular clouds could exist in space when the ultraviolet parts of stellar light can easily destroy them. Prof. van Dishoeck's famous and much-cited PhD thesis showed how abundant molecules like molecular hydrogen and carbon monoxide (CO) could protect the interior of a cloud through a process called "self-shielding". This research led to several seminal papers on the chemical structure of diffuse interstellar clouds.

Prof. van Dishoeck has frequently exploited cutting-edge observational facilities, especially in the infrared and (sub-)millimetre wavelength ranges. She pioneered mid-infrared spectroscopy in star-forming interstellar clouds and discovered the presence of key organic molecular species locked in ices on grains. Her research revealed that icy grains are effective factories of pre-biotic organic molecules, ensuring that these species are present in significant amounts when terrestrial planets are formed.

Prof. van Dishoeck and her teams have studied in detail the formation and evolution of protostellar disks with ground and space state-of-the-art observatories at submillimeter and infrared wavelengths, tracing in particular the path of water from interstellar clouds, via collapsing cores, to planet-forming disks. Her masterful application of spectroscopic tools across a broad range of wavelengths, with a superb exploitation of the most capable astronomical measurement techniques, and increasingly powerful theoretical modelling have brought the goal of understanding the formation of solar systems many steps closer.

She led the Leiden Laboratory for Astrophysics from 1992-2005, in which experiments are conducted to simulate the chemical processes in and on icy grain mantles. She now leads the development of sophisticated physical-chemical models of gas-phase and gas-grain chemistry from the small to large scales, linking the observations and basic processes.

In addition to her groundbreaking scientific work, Prof. van Dishoeck has been an active and vital member of the astronomical community. As president of the International Astronomical Union, she led the celebrations for its centenary in 2019; the more than 5000 public and scientific activities reached millions of people worldwide. She also co-curated that year an exhibition on Cosmos: Art & Knowledge. She has been a strong advocate for a number of large billion-Euro ground and space-based observational facilities that push the studies of the molecular universe to unprecedented levels. These include ALMA and the Herschel and MIRI/JWST satellites. Her science vision, leadership, and political skills enabled her to play key roles in all phases of these projects. The trust that the community has in her judgement is also apparent from her memberships of the deciding bodies of ESA and review committees of top astronomical research institutes.

Her unique and high impact research has made Ewine van Dishoeck the leading and most influential observational astrochemist in the world, as demonstrated her citation numbers: over 670 published papers, cited nearly 50,000 times, with an h-index of 115, one of the highest of the entire astronomical community.

Photo credit : Bram Belloni

MERAC Prizes

FONDATION MERAC (Mobilising European Research in Astrophysics and Cosmology) is a non-profit foundation started in 2012 with headquarters in Switzerland to recognise and support young European astronomers.

There are yearly three MERAC Prizes awarded by the European Astronomical Society. The prizes of 25'000 € are for each of the three categories:

- ★ Theoretical Astrophysics
- ★ Observational Astrophysics
- ★ New Technologies (Instrumental/Computational/Multi-Messenger)

The prizes alternate by year for:

- ★ Best Early Career Researcher Prizes (on odd years)
- ★ Best Doctoral Thesis Prizes (on even years)

The awardees are also eligible for further support from the FONDATION MERAC.

Best PhD Thesis in Theoretical Astrophysics

The 2022 MERAC Prize for the Best PhD Thesis in Theoretical Astrophysics is awarded to **Dr Helmer Koppelman (the Netherlands)** *for his multi-faceted approach to the field of galactic archaeology that transformed our understanding of the history and dynamics of the Milky Way.*

Dr Helmer Koppelman studied astrophysics at the University of Groningen, obtaining his MSc in 2016 « cum laude » with a thesis on the evolution of gaps in cold stellar streams. Dr Koppelman defended his PhD thesis at the University of Groningen in 2020 with the judicium « cum laude ». In his remarkably extensive and broad thesis, Dr. Koppelman combined theory, simulations, and vast datasets to yield new light on the structure and dynamics of the Milky Way halo and revolutionary new insights on its formation history. He spent a postdoc at the Institute for Advanced Study in Princeton and moved back to the Netherlands to start a new career as data scientist in an international company.

Dr Koppelman has produced an outstanding thesis on the formation and dynamics of the Galactic halo. The thesis offers new insights on how the Milky Way formed based on the newest datasets available and presents new modelling efforts and provides also a new characterization on the properties of dark matter halo of the Milky Way. Using Gaia DR2 data he discovered of a blob of stars that make up the local Galactic halo, which has been interpreted in terms of a large merger event that took place about 10 Gyr ago.

He further pushed the boundaries by fully exploiting the whole Gaia DR2 dataset, using the 1.3 billion stars with proper motion information to construct the biggest sample of halo stars currently available. Using data-mining tools, Dr Koppelman obtained the most precise lower limit to the mass of the Milky Way. In his thesis he further investigated the use of orbital frequencies to understand the gaps in narrow stellar streams, with as goal to put limits on the presence and properties of (dark matter) clumps in the halo.

Dr Koppelman's thesis excelled in the rigor of the analysis and detailed attention to uncertainties while keeping the broad overview of the scientific results and implications. Whereas most of the techniques were known, they were applied in rigorous way to totally new data with careful inference supported in an innovative way by insights from numerical simulations.

The PhD thesis of Dr Helmer Koppelman was conducted at the Kapteyn Astronomical Institute (Univ. of Groningen), under the supervision of Profs. Amina Helmi and Eline Tolstoy.

Best PhD Thesis in Observational Astrophysics

The 2022 MERAC Prize for the Best PhD Thesis in Observational Astrophysics is awarded to **Dr Núria Miret Roig (University of Vienna, Austria)** *for the discovery of many new free-floating planets, which illuminated the origin of these exotic nomad planets.*

Dr Miret Roig received a BSc in Physics and a MSc in Astrophysics from the University of Barcelona and obtained her PhD in 2020 from the University of Bordeaux, France, who also rewarded it with the Science and Technology Thesis Prize. Dr. Miret Roig expertise includes acquiring and analyzing massive observational datasets of nearby, young stars to derive fundamental properties such as the initial mass function, the spatial distribution, and the kinematics and dynamics of these systems. She has been co-PI of several successful proposals at major telescopes such as the GTC, VLT and CTIO, and led several studies of different aspects of the star formation process. Dr Miret Roig moved recently to a postdoc position at the University of Vienna, where she investigates the formation and origin of young stars in the solar neighbourhood.

Dr Núria Miret Roig's thesis presents the discovery of about a hundred new free-floating planets (FFPs) in the region encompassed by the Upper Scorpius stellar OB association and the Ophiuchus star-forming region. This sample is the largest ever discovered and constitutes an important step in setting the FFPs class and uncovering the origins and characteristics of these mysterious galactic nomads. Dr. Miret Roig demonstrated, for the first time, that the gravitational collapse of small clouds alone cannot explain the large fraction of observed FFPs. Instead, Dr. Miret-Roig thesis showed that an important fraction formed like planets but were ejected due to dynamical interactions.

Dr Miret Roig led an international team to combine images in public astronomical archives with new deep wide-field observations obtained with the best infrared and optical telescopes in the world, to measure proper motions and photometry of tens of millions of sources in a large area of the sky (171 square degrees). Dr. Miret-Roig used modern statistical and data mining techniques to identify the few thousands of stars and planets belonging to the young stellar association against the millions of background stars and galaxies. She obtained the mass function across four orders of magnitude for two regions of different ages (<10 Myr and 30 Myr), which now serve as a benchmark for defining the FFPs class, comparing to other regions, and testing theoretical models. Additionally, she presented a new methodology to determine the ages of young stellar associations based on their kinematics, in particular stemming from Gaia data. Dr Miret Roig has finished her PhD in three years with five articles as first author in high impact reviews.

The PhD thesis of Núria Miret-Roig was conducted at the Laboratoire d'Astrophysique de Bordeaux, University of Bordeaux (France), under the supervision of Prof. Hervé Bouy and Dr Javier Olivares.

Best PhD Thesis in New Technologies (Instrumental)

The 2022 MERAC Prize for the Best PhD Thesis in New Technologies (Instrumental) is awarded to **Dr Ewelina Obrzud (Centre Suisse d'Electronique et de Microtechnique, Switzerland)** *for the development of novel laser frequency combs for the accurate calibration and extreme radial velocity-precision of astronomical spectrographs.*

Dr Ewelina Obrzud graduated from the University of Geneva, Switzerland with a Master degree in Physics (specialisation in Astrophysics), and obtained in 2019 an interdisciplinary doctoral thesis (extra-solar planets and instrumentation) from the same university in collaboration with the Centre Suisse d'Electronique et de Microtechnique (CSEM), focussing on building and demonstrating alternatives for the existing laser frequency comb systems for astronomy. The quality of her thesis led her to be granted the Edith Alice Müller Award in 2020 by the Swiss Society for Astrophysics and Astronomy. Dr Obrzud has recently been promoted research & development engineer at CSEM.

In her PhD, Dr Obrzud developed two novel laser frequency combs for a precise and accurate calibration of extreme-radial-velocity-precision astronomical spectrographs. Both solutions are based on technologies providing laser pulses at ultra-high repetition rate (>10 GHz), a major challenge from a laser physics perspective but essential for spectrograph calibration. The first system, the electro-optic frequency comb, is characterized by an all-optical fibre-based design and simple architecture. The second system is based on dissipative Kerr soliton generation in optical microresonators. Dr Obrzud tested both systems, the electro-optic and Kerr frequency combs on astronomical spectrographs, demonstrating « real-life » operability and performance. She extended the scope of her work to a technique for frequency comb generation in the visible wavelength range, with a novel technique relying on triple-sum frequency generation in a nonlinear optical waveguide.

Dr Obrzud's work resulted in several peer-reviewed publications, four of them as first author, two of which in a Nature sub-journal. She also participated to international topical conferences and presented her results through talks and posters in conferences and workshops related to precise radial-velocity measurements and high-fidelity spectroscopy. Dr Obrzud's thesis work offers interesting solutions and concrete perspectives for the improvement of existing and future extreme-precision spectrographs for astronomy. While guided by the astronomical application, Dr Obrzud's work also attracted the attention of a wider interdisciplinary community including in particular those concerned with optical precision spectroscopy and nonlinear microphotonics.

The PhD thesis of Ewelina Obrzud was conducted at the Centre Suisse d'Electronique et Microtechnique (CSEM) in Neuchâtel and at the Department of Astronomy of the University of Geneva, under the supervision of Prof. Francesco Pepe, Dr François Wildi, and Dr Tobias Herr. The doctor title of « Dr es sciences » was granted by the University of Geneva with the tag 'Interdisciplinaire'.