TOWARDS REAL COMPARATIVE PLANETOLOGY: SYNERGIES BETWEEN SOLAR SYSTEM SCIENCE AND THE DARWIN MISSION

H. Lammer[1], E. Chassefière[2], Yu. N. Kulikov[3], F. Leblanc[4], H. I. M. Lichtenegger[1], J.-M. Grießmeier[5], M. Khodachenko[1], D. Stam[6], C. Sotin[7], I. Ribas[8], F. Selsis[9], F. Allard[9], I. Mingalev[3], O. Mingalev[3], H. Rauer[10], J. L. Grenfell[10], D. Langmayr[1], G. Jaritz[11], S. Endler[11], G. Wuchterl[12], S. Barabash[13], H. Gunell[13], R. Lundin[13], H. K. Biernat[1,11], H. O. Rucker[1,11], F. Westall[14], A. Brack[14], S. J. Bauer[11], A. Hanslmeier[11], P. Odert[11], M. Leitzinger[11], P. Wurz[15], E. Pilat-Lohinger[16], R. Dvorak[16], W. W. Weiss[16], W. von Bloh[17], S. Franck[17], T. Penz[1,11], A. Stadelmann[5], U. Motschann[5], N. K. Belisheva[18], A. Bérces[19], A. Léger[20], C. S. Cockell[21], J. Parnell[22], I. L. Arshukova[23], N. V. Erkaev[23], A. A. Konovalenko[24], E. Kallio[25], G. Horneck[26], T. Guillot[27], A. Morbidelli[27], E. Bois[27], P. Barge[28], M. Deleuil[28], C. Moutou[28], F. Forget[29], B. Érdi[30], A. Hatzes[31], E. Szuszkiewicz[32], and M. Fridlund[33]

[1]Space Research Institute (IWF), Austrian Academy of Sciences, Graz, Austria
[2]Service d'Aéronomie, Pôle de Planétologie (IPSL/CNRS), Paris, France
[3]Polar Geophysical Institute, Russian Academy of Sciences, Murmansk, Russian Federation
[4]CNRS, Service d'Aéronomie, Verrières Le Buisson, France
[5]Technische Universität Braunschweig, Germany
[6]Astronomical Institute Anton Pannekoek, University of Amsterdam, The Netherlands
[7]Laboratoire de Planétologie et Géodynamique (UMR-CNRS), Nantes, France
[8]Institut d'Estudis Espacials de Catalunya and Instituto de Ciencias del Espacio, Barcelona, Spain
[9]Centre de Recherche en Astrophysique de Lyon, and Ecole Normale Supérieure, Lyon, France
[10]DLR, German Aerospace Centre, Institute of Planetary Research, Berlin
[11]Institute for Physics, University of Graz, Austria
[12]Astrophysical Institute and University Observatory, Jena, Germany
[13]Swedish Institute of Space Physics, Kiruna, Sweden
[14]Centre de Biophysique Moléculaire, CNRS, Orléans, France
[15]Physikalisches Institut Bern, University of Bern, Switzerland
[16]Institute for Astronomy, University of Vienna, Austria
[17]Potsdam Institute for Climate Impact Research, Potsdam, Germany
[18]Polar Alpine Botanical Garden Institute, Russian Academy of Sciences, Apatity, Russian Federation
[19]Biophysics Research Group, Hungarian Academy of Sciences, Budapest, Hungary
[20]Institut d'Astrophysique. Spatiale, CNRS, Univ. Paris-Sud, Orsay, France
[21]Planetary and Space Sciences Research Institute, Open University, Milton Keynes, UK
[22]Dept. of Geology and Petroleum Geology, University of Aberdeen, Aberdeen, UK
[23]Institute for Computational Modelling, Russian Academy of Sciences, Krasnoyarsk, Russian Federation
[24]Institute of Radioastronomy Chervonopraporna, Ukrainian Academy of Sciences, Ukraine
[25]Finnish Meteorological Institute, Helsinki, Finland,
[26]DLR, Institute of Aerospace Medicine, Radiation Biology Section, Köln, Germany
[27]Observatory de la Côte d'Azur, Nice, CNRS, France
[28]Laboratoire d' Astrophysique de Marseille, France,
[29]LMD / CNRS, University P.& M. Curie, Paris, France
[30]Department of Astronomy, University of Budapest, Hungary
[31]Thüringer Landessternwarte Tautenburg, Germany
[32]Institute of Physics, University of Szczecin, Szczecin, Poland
[33]ESA/ESTEC, Nordwijk, The Netherlands

Abstract

Understanding the principles that generates Earth's long-time habitable environment compared with other Solar System bodies like Mercury, Venus, Mars, Titan, requires a space mission like DARWIN which is designed for the spectroscopic characterization of atmospheres and the search for biomarkers in terrestrial exoplanets. In this work, we point out that precursor studies to examine terrestrial exoplanets in terms of their origin, physical characteristics and the evolution of their atmospheres, opens a great opportunity for generations of experienced theoreticians and young scientists in the fields of astrophysics, planetology, atmospheric physics, space plasma physics, magnetospheric physics, solar physics, climate physics, chemistry, biophysics, and biology. We suppose that the synergy of these studies and future discoveries by DARWIN will enhance our knowledge how the Solar System and the biosphere on Earth evolved.

Key words: terrestrial exoplanets – comparative planetology – atmospheric physics – habitability – DARWIN

1. Introduction

We live in exciting times each month more and more exoplanets are discovered by various ground based planet search methods. With the discovery of 155 planets[1] outside our own Solar System, modern science is continuing the Copernican revolution, placing our planetary system among a wealth of systems existing in the Universe. Although most of the discovered exoplanets have masses more comparable to the gas giants in the Solar System like Jupiter (Jupiter is 318 times more massive than the Earth) than rocky Earth-like planets, due to technical advances, observers are starting also to discover lower mass non-Jupiter-class exoplanets.

Recently, with the installation of the new HARPS spectrograph at the 3.6 m ESO telescope in La Silla, Chile a significant quantitative advance for European planet-finding programs has been possible. The level of precision in radial-velocity measurements achieved with HARPS gives the possibility of lowering significantly the detection limit to the *few-Earth-mass* regime. In fact, Santos et al. (2004) discovered a 14-Earth-mass exoplanet orbiting the Sun-like star μArae at about 0.1 AU. This detection represents the first discovery of an exoplanet with a mass slightly smaller than that of Uranus, the smallest *ice giant* in the Solar System.

In June 13 2005, the discovery of the first terrestrial exoplanet with 7 times the mass of Earth in an orbit of about 0.021 AU around the red dwarf star Gliese 876 was reported by Rivera et al. (2005). Planets with masses $\leq$ 10 Earth-masses are thought to be rocky terrestrials, while planets with masses $>$ 10 Earth-masses are more gaseous, since their stronger gravity can collect and retain more gas during planetary formation. The host star Gliese 876 is an M-type dwarf star with a luminosity of about 600 times less than that of our Sun. The expected surface temperatures of the first discovered terrestrial exoplanet resembles more Mercury's than the Earth's temperature.

The CoRoT (CNES) space observatory to be launched in 2006 (Fig. 2) is the first space mission, which will use high precise photometry for planetary detection by the transit method. Theoretical precursor studies show that exoplanets with sizes from 2 Earth-radii and larger appear clearly within the detection capabilities. One can, therefore expect that CoRoT will discover several super-Earth's from 2006 onward, which will be followed by the detection of Earth-size exoplanets by NASA's Kepler mission.

However, these discoveries lead astronomers and planetary scientists to a stage where one can seriously address one of mankind's *big questions*: *Are we alone in the Universe?* This issue that has been with mankind since antiquity, it carries a weight, which impacts all of society from the philosopher in the academic halls to science fiction movies.

[1] Exoplanet status, June 15, 2005: 136 planetary systems; 155 discovered exoplanets; 14 multiple planetary systems; http://vo.obspm.fr/exoplanetes/encyclo/catalog.php

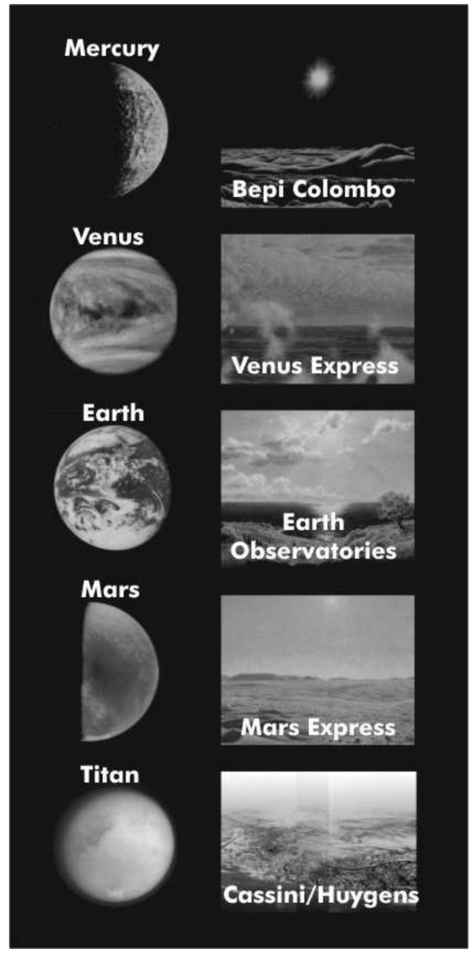

Figure 1. Illustration of the terrestrial planets in our Solar System and Saturn's satellite Titan, which are being explored at present or in the near future by European spacecraft.

At the heart of the problem is, of course the realization, that by understanding how our own Earth and the evolution of its biosphere, compared to other terrestrial planets like Venus or Mars, fits into the greater scheme of things, we will reach a greater understanding about ourselves. For understanding why Earth evolved different, than the other terrestrial bodies in the Solar System (see Fig. 1), European space missions to Mars, Venus, Mercury and Saturn's satellite Titan have been or will be carried out (Mars Express: successful in orbit around Mars since 2003; Huygens successful decent and landing on Titan, 2005; Venus Express: Venus: launch October 2005, Bepi-Colombo: Mercury, launch 2012). Many important questions have to be answered:

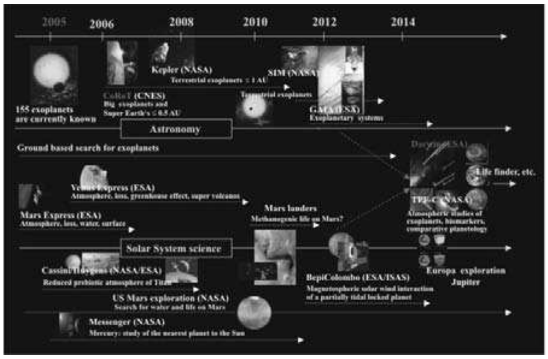

Figure 2. Illustration which shows the synergy effect of DARWIN-like missions between various astronomical planet-search projects and Solar System missions.

– Why has Mars lost its atmosphere and water compared to Earth?
– When did Mars lose its magnetic field?
– Did life also evolve on early Mars?
– Is Titan's prebiotic atmosphere representative of the early Earth atmosphere?
– Is there lightning in Titan's atmosphere, which acts as an energy source for prebiotic chemistry?
– Did Titan lose much of its atmosphere during the active early period of the young Sun?
– Was early Venus wet?
– How did the greenhouse effect evolve on Venus?
– How does the solar wind interact with an Earth-like planet (Venus) whose atmosphere is not protected by a magnetosphere?
– How much atmosphere could have been lost from early Venus?
– Did early Mercury have an atmosphere?
– What can we learn from the impact history on Mercury?
– How is Mercury's magnetic field generated?
– What is the reaction of Mercury's exosphere and magnetospheric environment to strong solar wind plasma, flares and coronal mass ejections (CMEs)?

At the same time, technology is advancing rapidly enough to the stage, where we will be able to observe extrasolar planetary systems like our own at interstellar distances. As one can see in Fig. 2 the search and characterization of exoplanets like our own is a great prize in the global quest for knowledge.

The search for terrestrial exoplanets has indeed been identified in the long term plan of ESA (ESA Millennium Long Term Plan, ESA SP-2000) as the first of its 20 priority actions. Furthermore, the Cosmic Vision 2015-2025 development plan has identified "other worlds and life in the Universe: placing the Solar System into context" as a major theme. One can see from the illustration in Fig. 2 that a DARWIN-like mission will lead to a synergy between the astrophysics and planetary science communities and will initiate an age where real comparative planetology will become a reality, because the main high level objectives for such a mission illustrated in Fig. 3 are:

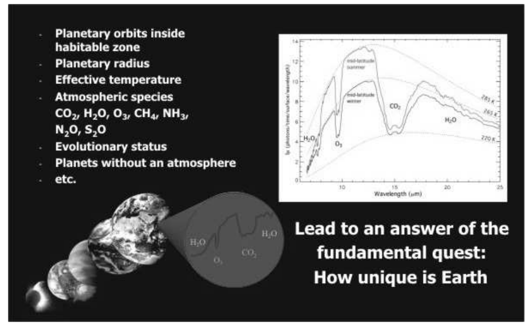

Figure 3. Illustration, which shows the main scientific objectives of the DARWIN mission.

– To survey nearby stars for terrestrial planets (i.e., planets similar to Venus, Earth and Mars), orbiting within the habitable zone of each star.
– To study any planets found in detail in terms of composition, orbital mechanics, geophysical conditions.
– To study the atmospheric composition and determine its evolutionary status compared to the terrestrial planets in our Solar System.
– To search any detected planetary atmosphere for signs of biological activity as we know it (commonly called biomarkers), or their precursors.
– To compare discovered planetary atmospheres around different star types (F, G, K, M)
– To characterize star-types and orbital distances of planets without atmospheres to planets with atmospheres.

These objectives will undoubtedly be the foundation of real comparative planetology. With comparative planetology we here mean the investigation on how different planetary systems and their individual planets - and particularly Earth-like ones - are formed, how they evolve in their interaction with their host star under different circumstances, how often they give rise to conditions that could in principle be benevolent enough for the origin of life to occur, and even whether life as we know it could have arisen on any world near the Earth.

In the following Sections of this work, we show that the application of:

– atmospheric models,
– climate models,
– photochemical models,
– radiation transfer models,
– MHD, test particle and hybrid models for studying solar/stellar wind interaction processes,
– magnetospheric models,
– geological models,

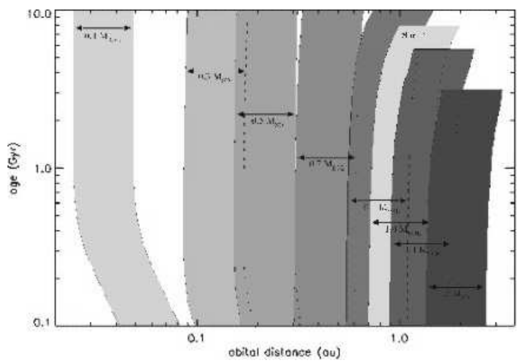

Figure 4. Examples of boundaries of the HZ for main-sequence stars of different masses as a function of the stellar age.

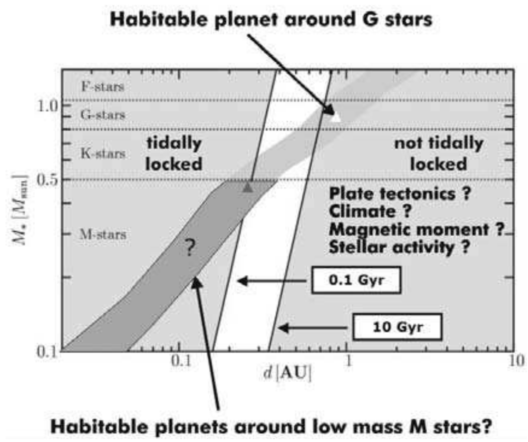

Figure 5. The inner border of the white area indicates that an Earth-like planet will be tidally locked after 0.1 Gyr, while the outer border corresponds to a tidal locking time of about 10 Gyr.

– geodynamic models,

developed and currently applied to the planets in our Solar System are important for precursor science, relevant to the characterization of terrestrial exoplanets, which will be discovered in the coming decade.

2. Planetary habitability

2.1. The habitable zone

The circumstellar habitable zone (HZ) of a star is currently defined under the constraint that a planet of the size and mass by Earth contains large amounts of H_2O and CO_2 reservoirs at a certain distance from its host star (see Fig. 4). If there is an amount of atmospheric CO_2 able to sustain stable liquid H_2O at the planetary surface, that distance belongs in the HZ.

If the distance is below a critical value, the planet would experience a runaway greenhouse effect like Venus. At the outer border of the HZ, an increase in the CO_2 pressure results in surface cooling more than heating, due to enhanced Rayleigh back-scattering of the incoming stellar radiation to space. With this definition, the HZ depends on the stellar luminosity and the surface temperature, which is assumed to be stabilized slightly above zero degree by the carbon-silicate cycle that controls the partial CO_2 pressure.

Although this general definition of the HZ can be applied to all stellar types, the atmospheric evolution of terrestrial planets in the HZ of M, K and F stars will be different, so that our present view of the HZ is incomplete. Low mass M and K stars have closer orbital locations for planets in the HZ, longer active XUV periods, and different stellar winds than solar-like stars. As shown in Fig. 5, terrestrial exoplanets inside the HZ of these stars can be partially or totally tidally locked - impacts to their climate, plate tectonics and magnetic dynamos are expected. Therefore, additional questions regarding planetary habitability of close-in terrestrial exoplanets which can be studied by a DARWIN-like mission have to be considered.

2.2. Climate studies

The consequences of such a situation on climate can be dramatic: Studies with General Circulation Climate Models (GCMs) indicate that the atmospheric stability of tidally locked terrestrial planets orbiting dwarf stars depends on the landmass and the available amount of water. However, the atmosphere has to be formed before the planet is tidally locked and maintained throughout its whole lifetime. Moreover, other questions remain to be answered:

– Are there unknown feedback processes, which can stabilize the atmospheric pressure in the inner part of the habitable zone?
– Is a tidally locked planet able to recover from a snowball event as Earth may have done several times during its history?

However, as illustrated in Fig. 6 more applications of self consistent chemical GCMs have to be applied. The results of such studies will also enhance our understanding of climate-change processes on Earth and how life can influence and change an atmosphere.

2.3. Plate tectonics

The cycling of volatiles by plate tectonics helps to regulate the composition of the Earth's atmosphere, including the greenhouse gas CO_2 and hence the surface temperature and planetary habitability. Plate tectonics is also important to life on Earth by the creation of land surfaces, enhancement for biodiversity through evolution on

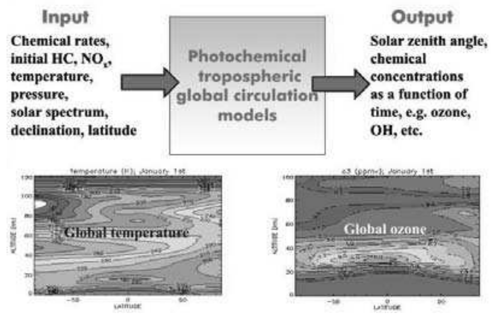

Figure 6. Illustration of the application of coupled chemistry-climate models and GCMs, currently used for comparative planetology on Venus, Earth, Mars and Saturn's satellite Titan. It is important to expand such studies to terrestrial exoplanets, because different radiation and particle fluxes related to different host star-types will effect the climate, chemistry and expected biomarkers.

isolated continents, and is an important factor in generation mechanisms of intrinsic planetary magnetic dynamos. The controls on plate tectonics are not known with certainty, but the minimum requirements may be:

– sufficient mass (and hence heat flow) to drive mantle convection,

and

– water to lubricate plate motion.

Both processes are likely to be essential: Venus, for example, has an Earth-like mass but a lack of water, which may explain the lack of plate tectonics. Tidal locking could also have a significant influence on large-scale convection in the planetary mantle and may inhibit plate tectonics partially or completely. Tidally locked planets, which could not develop plate tectonics may produce various life frustrating scenarios like:

– periodical outbreaks of Venus-type super volcanoes (hot plumes),
– different atmosphere-surface interaction processes, which may have an impact on the CO_2 cycle of a terrestrial planet,

and

– due to slow rotation, weak intrinsic magnetic moments.

However, exact answers to all of these questions require detailed modelling and observational studies of slow-rotating planets like Mercury, Venus or tidally locked satellites like Titan.

2.4. Magnetic moments

Another important aspect, which can have a strong effect on planetary habitability, is weak or no planetary magnetic moment. Commonly employed scaling-laws for planetary magnetic moments yield rapidly decreasing moments with decreasing rotation rates. This is why small magnetic moments seem likely for close-in exoplanets.

At first glance, a uniform generation mechanism for magnetic moments seems absurd, but it is likely to appear that there is such a mechanism, which acts presently in different phases for the individual planets. This basic mechanism is likely to be a dynamo process related to necessary conditions like liquid regions, convection, and conductive materials.

Energy sources may vary and the thermal history differ certainly through the different sizes of the bodies. Three different phases of magnetic activity can be observed in the Solar System:

– a pre-dynamo phase (Venus),
– a dynamo phase (e.g., Earth, Mercury),
– a post-dynamo phase (Mars, Moon).

Terrestrial planets mainly consist of material which condenses at high temperatures such as metallic iron, oxides and silicates of iron, resulting in iron-rich cores. These cores are at least partially liquid even after 4.5 Gyr of cooling. Convection requires that the Coriolis force has a large effect on the flow. This condition, however, is easily satisfied, even for the case of slow rotating planets like Venus. Thus, the question is not whether the planets can sustain a dynamo, but how strong this magnetic field can be.

By knowing the size of a terrestrial planet discovered by DARWIN and the mass determined by the radial velocity method or obtained by the SIM mission in the case of planets close to their host stars the application of planetary composition and internal structure models can be used for the calculation of core-sizes.

– If the size of the core is known, the magnetic moment of the planet can be estimated by model simulations.

2.5. Orbital dynamics

In addition, general questions regarding the origin and frequency of terrestrial planets, water delivery and the role of giant planets in their formation scenario, as well as their long-time orbital stability and dynamical evolution inside the HZ in multiple planetary systems, have important roles in understanding the evolution of habitable planets.

All extra-solar planetary systems discovered so far are dynamically very different from the Solar System. In most cases, gas giants are close to their central star and many of them have very eccentric orbits, which sometimes approach each other very closely or even intersect in space. These two facts lead to very strong planetary gravitational interactions and as a result can lead to chaotic, unstable dynamical behaviors of hypothetical terrestrial planets in the HZ of their host stars.

– The existence of resonance-like factors to the robustness of orbital stability makes this one a criterion of lifespan of planetary systems and is important for the evolution of habitable terrestrial planets.

Model simulations related to the presence or lack of resonances in planetary systems can be used to set up a first criteria of dichotomy hence a hierarchical classification of planetary systems.

3. Stellar-planetary relations

3.1. The target stars

Another main question which a DARWIN-like mission must address is: which star-types (F, G, K, M) may be good, or preferred candidates in the search for habitable terrestrial exoplanets? A problematic point in the target star selection of terrestrial planet finding missions is that they are technologically limited to nearby target stars in the distance range (10–30 pc). A coronagraph design like NASA's TPF-C is restricted to closer stars (<10 pc), whereas a space interferometer as planned for DARWIN should be able to observe solar-like stars to the outer edge of this range (< 30 pc).

These objectives mean that we have to determine the prevalence of Earth-like planets around a large enough sample of at least 150 nearby Sun-like G-type stars to be statistically meaningful - particularly when considering evolutionary schemes. This will enable the determination of how common terrestrial planets are and what the status of our own Earth is in the context of physical principles governing the formation and subsequent evolution of such bodies.

– Also, other star-types can be studied by this mission, so that one can compare terrestrial planets discovered at systems similar to ours, with systems where the HZ is inside the tidal locking area, i.e., where Earth-like planets may be exposed by strong radiation fluxes, stellar winds or coronal mass ejections (CMEs).

3.2. X-ray, EUV and UV radiation

Because the spectral type of the star plays a major role in all atmospheric processes, the photochemistry and evolution of planetary atmospheres, as well as their planetary water inventories must be understood within the context of the evolving stellar energy and particle fluxes.

– Only stable atmospheres and water inventories over long time-spans will allow the evolution of biospheres.

Thermal escape of atmospheric constituents and atmospheric expansion depend on the stellar X-ray and EUV flux (XUV), which affects both, the temperature of the upper atmosphere and photoionization processes, it is important to know the time evolution of stellar radiation and particle fluxes.

We know from enriched heavy isotopes in the atmospheres of Venus, Earth, Mars, and Saturn's large satellite Titan, from radiative stellar fluxes, stellar magnetic fields, stellar winds of solar-type stars with different ages, and lunar and meteorite fossil records that the young Sun (a G-type star) underwent a highly active phase.

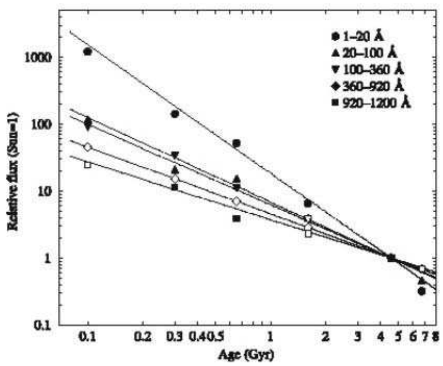

Figure 7. Solar-normalized fluxes vs. age for different stages of the evolution of solar-type stars. Plotted are here the measurements for different wavelength intervals (filled symbols) and the corresponding fits using power-law relationships. Represented with empty symbols are the inferred fluxes for those intervals with no available observations

Observations of solar proxies with various ages as shown in Fig. 7 indicate an active XUV phase of the young Sun (representative for G stars), with an XUV flux 6 times higher 3.5 Gyr ago. The young solar phase included continuous flare events, and XUV radiation up to 100 times more intense than today about 100 Myr after the Sun arrived at the ZAMS. Recent studies on K type stars show that they stay at active emission levels for somewhat longer than G stars and afterwards also decrease following a power law relationship. Interestingly, early M-type stars appear to stay at high levels until ages ≥ 1 Gyr, and then decrease in an analogous way to G and K stars. Furthermore, observations indicate that early K stars and early M stars may have XUV emissions that are about 3–4 times and about 10–100 times higher, respectively, than solar-type G stars of the same age.

The relevant wavelengths for the heating of upper atmospheres are the ionizing ones ≤ 100 nm, which contain only a small fraction of the stars' spectral power but can lead to extended upper atmospheres and planetary winds triggered by hydrodynamic conditions, as observed by the hydrogen-rich short periodic Jupiter-class exoplanet HD209458b. When a large amount of XUV energy is deposited at the top of an atmosphere, heated atoms (preferably light constituents, while a high CO_2 content may prevent hydrodynamic condition due to IR-cooling - see Fig. 8) can overcome the planetary gravity field and expand into the interplanetary space. As one can see from Fig. 7 and Fig. 8, the X-ray and EUV radiation of young G-type stars including our Sun should have a

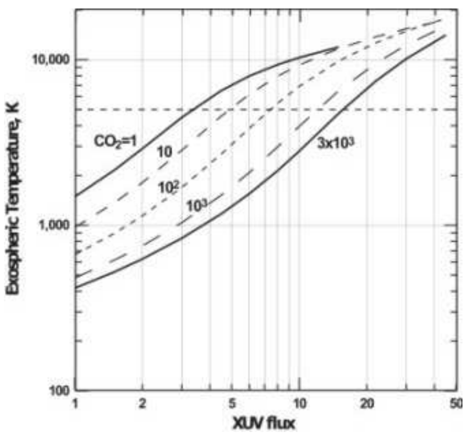

Figure 8. Temperature profiles in an Earth-like exosphere for different levels of CO_2 abundance, and XUV flux values in the thermosphere. The numbers on the curves correspond to CO_2 volume mixing ratios expressed in PAL (present time atmospheric level). 1 PAL for $CO_2 = 3 \times 10^{-4}$; 10 PAL = 0.3%, 100 PAL = 3%, 1000 PAL = 30%. Atmospheric levels of the N_2, O_2, and O content are all specified to be 1 PAL. Only the 15 μm CO_2 cooling is present in this simulation. The horizontal dashed line shows the so-called "blow off" temperature of atomic hydrogen.

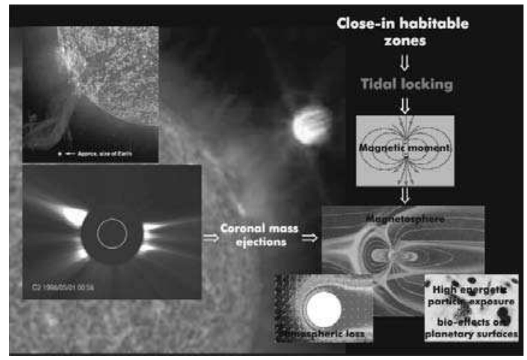

Figure 9. Illustrations of the expected impact of stellar CMEs for terrestrial exoplanets in orbits of close-in HZs of low mass M and K type stars.

strong impact on the chemistry, heating and loss of upper atmospheres.

- Therefore, studies related to the evolution of the early atmospheres of Venus, Earth, Mars and Titan as well as terrestrial exoplanets have to include the change in solar/stellar radiation fluxes with time.

High XUV radiation on saturation levels up to several 100 Myr and even Gyr of M stars may result in large exospheric temperatures on terrestrial exoplanets. This may have a strong impact on atmospheric stability, evolution of their water inventories and planetary habitability.

A further question regarding the evolution of life on planetary surfaces is, whether different UV fluxes can be responsible for positive or negative evolutionary developments, like in the context of high UV radiation on an O_2 and O_3 free atmosphere like on early Earth.

- Different star-types have different UV fluxes compared to the Sun, which result in different photochemistry in the atmospheres and biological effects on the surfaces of terrestrial planets.

3.3. Stellar winds

The evolution of the solar/stellar wind mass flux as a function of time has also important implications for the evolution of planetary atmospheres. Recent HST high-resolution spectroscopic observations of the H Lyman-α feature of several nearby solar-like G and K main-sequence stars have revealed neutral hydrogen absorption associated with the interaction between the stars' fully ionized coronal winds and the partially ionized local interstellar medium.

It was found from a small sample of solar-like stars, where astrospheres can be observed, that stellar mass loss rates increase with stellar activity. The correlation between mass loss and X-ray surface flux follows a power-law relationship, which indicates an average stellar wind density up to 1000 times higher than today during the first 100 Myr after the Sun reached the ZAMS. However, to confirm this indications, more active young solar-like G and K stars with X-ray surface fluxes larger than 10^6 erg cm^{-2} s^{-1} should be studied in the future.

3.4. Coronal Mass Ejections

It is known from observations of our Sun that CMEs occur and propagate as dense and fast plasma structures through interplanetary space (Fig. 9). One can expect that dense plasma ejections like CMEs from target stars may strongly affect the atmospheres and magnetospheres of terrestrial exoplanets, especially at close-in HZs at orbit locations < 0.3 AU around low mass M stars. Because M stars are very active in X-rays, they are expected to have a high flare rate and hence CMEs should be common.

The recent application of a test particle model which was developed and successfully applied for the study of pick up ions on Mars and Venus, to the study of atmospheric erosion of Earth-like exoplanets inside the HZs at 0.05, 0.1 and 0.2 AU of M stars showed that these planets may lose atmospheres from 10s to 100s of bars depending on the strength of their magnetic dynamo and absorbed XUV radiation.

- The characterization of tidally locked planets without and with atmospheres around low mass stars by a DARWIN-like mission would give us an idea at which orbital distances terrestrial planets inside the HZ of

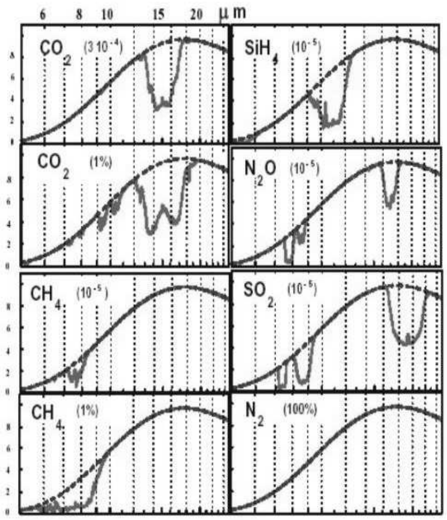

Figure 10. Various simulated spectra with different gas amounts (including biomarkers) related to studies of Earth-like exoplanets in various evolutionary stages.

dwarf stars can retain an atmosphere which may be related to the strengths of their magnetic dynamo - which is strong enough to balance the incoming CME and stellar wind plasma pressure.

Furthermore, because close-in terrestrial exoplanets are not protected by an extended Earth-like magnetosphere, energetic particles, which are related to CMEs and active regions of their host stars and cosmic rays can reach almost the whole surface area of the upper atmospheres. Under these conditions energetic particles can interact with the atmosphere where they change the chemistry, possibly even the O_3 content, and climate. Furthermore, if the pressure conditions are similar to those at Earth, secondary energetic particles can penetrate to the planet's surface where they will have an impact on biological systems.

3.5. Using DARWIN for studying early Earth

It is well known from satellite observations and from the output of coupled chemistry-climate models on Earth, that important physical factors like atmospheric temperature and solar radiation affect atmospheric biomarkers over diurnal and seasonal timescales.

Since we expect that a DARWIN-like mission will discover terrestrial exoplanets at different star-types and stellar/planetary evolution phases, one has to study how different radiation inputs and climate changes can affect biomarkers.

Because there are many solar-like stars ≤ 30 pc which are younger than the Sun, DARWIN could be used as a kind of time machine, if these systems harbor Earth-like

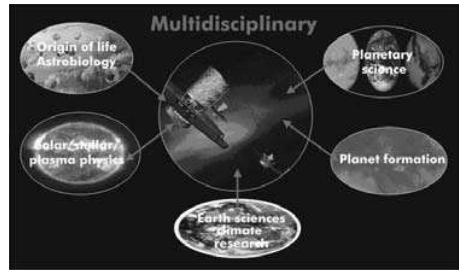

Figure 11. A DARWIN-like mission connects research related to planetary formation, planetology, atmospheric physics, solar and stellar physics, space plasma physics, and the origin of life, and is a perfect tool for real comparative planetology.

planets inside their HZs. The spectroscopic characterization of atmospheres of these planets and the search for biomarkers may allow us to study an Earth-like atmosphere under various evolutionary stages, including different atmospheric species (see Fig. 10).

4. Conclusion

As shown in Fig. 11, a multidisciplinary effort between the astronomy, planetary and biological communities will allow the detailed characterization of Earth-like planets beyond the Solar System. For finding constraining parameters for the existence of biospheres and the evolution of life in the Universe, atmospheric models, climate models, photochemical models, radiation transfer models, MHD, test particle and hybrid models for studying solar/stellar wind interaction processes, magnetospheric models, geological models, etc., which exist inside the European scientific communities have to be applied inside a strong precursor science program dedicated for the characterization of terrestrial exoplanets, which will be discovered by a DARWIN-like mission around 2015.

The application of the scientific expertise of European scientists from various planetary exploration missions and Earth science projects to the study of terrestrial exoplanets will enhance our present understanding of the evolution of the Earth and the other planets in our Solar System and will give European science and technology, as well as its society at large, a leading role globally.

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