Origins: From the Protosun to the First Steps of Life
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Cosmic Pathways to Life: From Interstellar Molecules to the First Traces of Life

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Abstract. The present-day Earth with its innumerable life forms is a product of cosmic evolution starting with the formation of our galaxy and the dense gas clouds within it, and proceeding through the contraction of one of those clouds about 4.6 Gyr ago, first into filaments and then one or more protostellar disks, planets, and central stars, one of which was our Sun. Radioactive debris from a massive nearby star was included. The planets themselves formed through coagulation, accretion, and fragmentation of solid bodies. Habitability depends on a delicate balance between disk accretion by gravity and dispersal by the central star, which determine the size of the planet and its gaseous envelope, combined with a long period of stellar radiation, which has to disperse this envelope but leave a hospitable secondary atmosphere. The final step toward life involves even more complexity as self-replicating bio-molecules form with ever increasing stability.

Keywords. astrobiology, astrochemistry, magnetic fields, Sun: activity, stars: activity, Earth, planets and satellites: formation, solar system: formation, stars: formation

1. Introduction

Observations of local interstellar clouds at infrared to millimeter wavelengths show solar-mass stars and their proto-planetary disks in the process of formation. The nearest disks seen at high resolution contain dust, gas, and ice with structures such as gaps or spirals suggestive of embedded planets and their dynamical processes. The last few years saw major advances in our view of interstellar cloud structures and the differences between low mass and high mass star formation, differences that may in fact be important for the eventual formation of terrestrial planets around solar-type stars.

Optical observations of thousands of stars up to fairly large distances in the Milky Way show periodic dips in brightness up to the percent level, indicating partially occulting planets with measurable sizes. Absorption spectra obtained during planetary transits have given first hints on the compositions of the planetary atmospheres. These advances over the last decade, combined with increasing complexity in computer modeling, bring us closer to visualizing how the Earth might have formed and what the conditions might have been like at its beginning.

The ultimate quest is not only about the origin of the Earth, but also about the origin of life on Earth. There has been progress on this topic also, but most of it has been outside the realm of astronomical observations. Still, there are increasingly sophisticated observations and modeling of possible life-related chemical reactions on other bodies in the Solar System, growing understanding of autonomous activities in RNA, DNA and other bio-molecules, and new physical explanations for what it means to be alive in a world governed by unshakable laws of physics.

This review is based on a plenary lecture by one of the authors (Manuel Güdel) at the General Assembly of the International Astronomical Union in Vienna Austria, delivered on August 22nd, 2018. A series of invited review and contributed talks accompanied this plenary lecture as part of IAU Symposium 345 on “Origins: from the formation of the Sun to the first steps of life.” We refer to these other talks here, as published in the present volume. They consider each topic in more detail and cover both observations and numerical modeling at a wide range of resolutions. This plenary talk also benefited from contributions by the Scientific Organizing Committee, as acknowledged below.

The key to life as we know it is the presence of liquid water, presumably on a solid, probably rocky, surface with an atmosphere above it. For the last several billion years, while life on Earth was developing, the conditions in this environment, the water, land and atmospheric pressure, have not changed much, giving the false impression that the Earth might have always been a hospitable planet. However, young solar-type stars are highly variable with strong winds and X-ray emission for their first tens to hundreds of Myr, planetary distances from their stars can change on timescales of 10 to 100 Myr, and outgassing from magma oceans and through volcanism as well as accretion from interplanetary bodies can change the physical conditions on the planet’s surface and even the composition of its atmosphere, especially during the first few hundred Myr of a planet’s life. The early Earth and other Earth-like planets may not have been so hospitable when proto-life was at its earliest stages. This means that a complete understanding of the origin of the Earth and life as we know it requires detailed astronomical observations of the conditions around other solar-like stars and their Earth-like planets.

2. Formation of the Sun

The Earth and Sun formed at about two-thirds of the present age of the Universe. Figure 1 shows a time line of the cosmic star formation rate (SFR), measured in solar masses per year per cubic Megaparsecs, averaged over all space (from Madau & Dickinson 2014). At early times, the SFR was low because most of the galaxies in which stars form were small. The rate reached a peak at around 10 Gyr ago and has been decreasing slowly ever since because the average density of the universe has been decreasing, and because an increasing fraction of the remaining cosmic gas has become too hot to fall onto the denser parts of galaxies where it can turn into cold clouds and collapse into stars. The peak SFR in our own galaxy, the Milky Way, occurred about 8 Gyr ago, and by the time the Sun and Earth formed, 4.6 Gyr ago, the Milky Way had quieted down by a factor of ~ 3 in its conversion of gas into stars. Life crawled up on land only ~ 0.5 Gyr ago, after living in the ocean for its first ~ 3 Gyr.

Galaxy mergers and cosmic gas infall are important parts of the history of star formation. Because a typical starburst lasts only a few hundred million years, star formation would have stopped early without the continued accretion of new material. It was during the later phase of quiescent accretion when the Solar System and early life formed, after most of the violent collisions with the young Milky Way ended.

Solar-mass stars form in a wide variety of environments, ranging from low-mass regions with only a few other stars to massive young stellar complexes and dense star clusters. The most massive complexes are relatively rare and the nearest examples are fairly distant, making them difficult to study in detail. Nearby examples of solar-mass star formation include the Taurus region at 140 pc (see the Symposium review by Mika Juvela). Figure 2 shows this region with several well-known objects identified, i.e., the

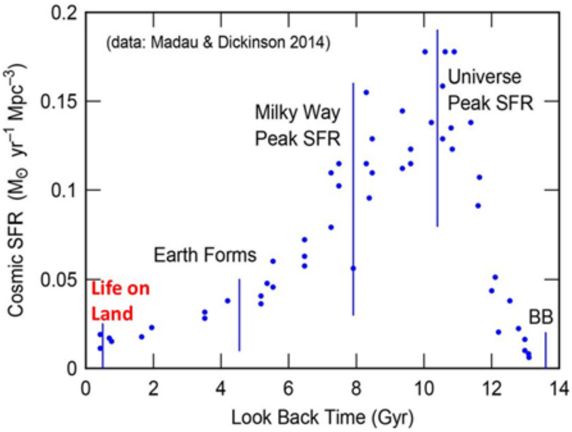

Figure 1. The history of star formation in the universe, averaged over space, from Madau & Dickinson (2014). The universe began with the Big Bang ("BB") around 13.7 Gyr ago, which is on the right-hand side of the plot. The star formation rate increased at first as star-forming galaxies grew in size. Then it decreased as the surrounding gas density decreased with the continued expansion of the Universe. It also decreased as infalling gas heated up in massive dark matter halos and became too hot to accrete onto the enclosed galaxy disks. The Milky Way formed as a small galaxy at first, reaching its peak star formation rate around 8 Gyr ago. The Earth and Sun formed when the Milky Way had quieted down to about one-third of its peak rate.

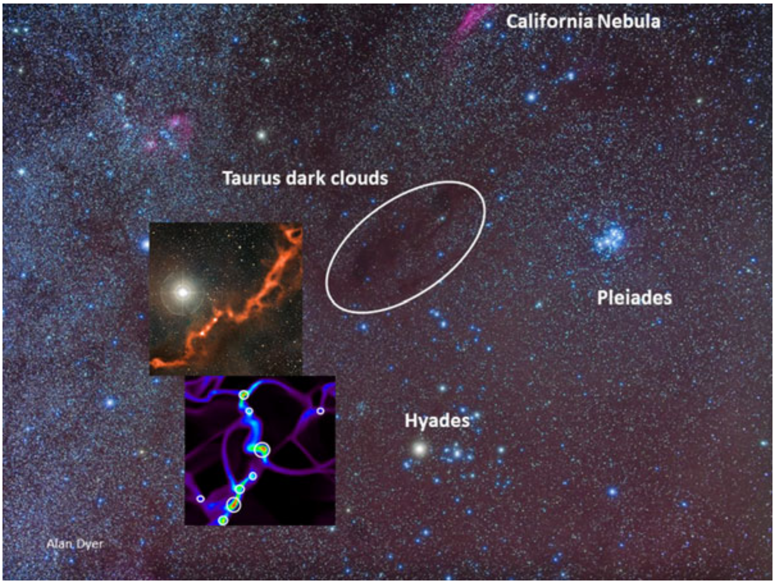

Figure 2. Sky view of the region around the Taurus dark clouds, including the Pleiades and Hyades star clusters. The Taurus clouds are filaments, like most star-forming clouds, with dense knots as the collection points where gravity brings the gas together. The insert on the left is an infra-red view from Hacar *et al.* (2013), and the insert below that is a numerical simulation of a turbulent cloud, from Paolo Padoan (private communication). The background star field is from Alan Dyer (https://amazingsky.net/2011/02/21/the-dark-clouds-of-taurus/).

Pleiades and Hyades clusters, with ages of ~ 100 Myr and ~ 600 Myr, and the California Nebula in the north, which is illuminated by the massive star ξ Persei. Shown inside a white oval are several dark filaments in which low-mass stars are currently forming. An inset on the left shows one of these filaments (the one running to the north-west approximately along the major axis of the ellipse of the oval, with a bright star next to it) glowing in the sub-mm light of cold dust emission (from ESO/APEX; Hacar *et al.* 2013). Several bright spots can be seen from embedded young stars. Also inset is an image from a numerical simulation of a star-forming filament, from Dr. Paolo Padoan (based on work in Padoan & Nordlund 2002). The similar structure results from shock formation in a supersonically turbulent fluid followed by gravitational collapse in the shock-compressed gas (see the Symposium review by Christoph Federrath). Dynamical feedback from young stellar objects maintains an overall low star formation efficiency, although it may be higher where bound stellar clusters form.

While the Taurus clouds are often used as an analogue for solar-type star formation, we now believe the proto-sun formed in a region with more massive stellar companions. The most suggestive evidence for this is the presence of the ^{26}Al decay product, ^{26}Mg, inside Ca and Al-rich inclusions in the most primitive type of meteorite, carbonaceous chondrites (see the Symposium review by Edward Young). ^{26}Al is formed by proton capture in the Mg-Al catalytic cycle of nuclear fusion, which occurs at high temperatures in massive stars. Its half-life is 0.7 Myr, which is so short that the Sun had to form in the midst of these massive stars, either in a massive complex with such stars also forming, or around massive complexes where the gas is contaminated by the semi-continuous production of this radioactive material through on-going star formation (see the Symposium chapter by Yusuke Fujimoto). The ^{26}Al and a few other radio-active elements in meteorites could have gotten into the Sun-forming gas via a supernova explosion that expelled these elements along with a lot of other mass when the massive star exploded, or via the winds from aging massive stars, such as Wolf-Rayet stars, which also carry along proton-capture nucleosynthetic byproducts (see the Symposium chapter by Vikram Dwarkadas). Among these two possibilities, supernovae may be less favored because radioactive iron that should come from a supernova, ^{60}Fe, does not appear to be abundant enough in meteorites.

If the Sun formed along with high mass stars, then regions like the Orion OB association have an increased relevance (see the discussions by Diederik Kruijssen and Michael Küffmeier in this volume.). Large scale surveys of the Galactic cold interstellar medium reveal a complex structure of elongated clouds with connecting striations and cold clumpy filaments, as reviewed by Mika Juvela in this volume. High resolution ALMA-based observations of the filaments resolve smaller filaments, or fibers, inside of them, possibly feeding the star-forming cores. Then the mass of the forming stars could depend on the local "fiber surface density" as suggested by Alvaro Hacar in this volume. In his examples, cluster-forming filaments in Orion present fibers with 2 orders of magnitude higher density than analogous fibers in Taurus. Methods to find and quantify filamentary structures are discussed in the paper by Maria Cunningham in this volume. Observations of dense, star-forming gas throughout the Milky Way are discussed by Quang Nguyen-Luong and gas accretion processes for local protostars are discussed by Ian Stephens in this volume.

Recent astrometric data from the Gaia satellite are now helping us find the former members of dispersed OB associations and understand the kinematics of young stellar clusters (see review by Anna Melnik in this volume). We are also witnessing a significant increase in our chances to link young stellar objects to interstellar clouds where they formed, as shown for Orion clusters by Josefa Elisabeth Grossschedl in this volume.

The remnants of ^{26}Al in carbonaceous chondrites are important not only for tracing the early environment of the Sun, but also for suggesting a significant heat source in

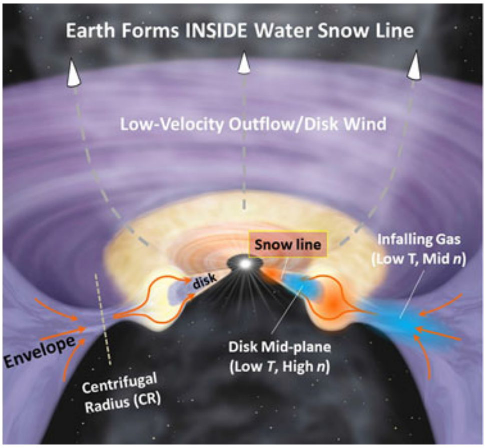

Figure 3. Schematic of a proto-solar disk showing the vertical structure in cross-section (from Yuri Aikawa) (Sakai *et al.* 2017, Credit: RIKEN/Japan). The inner region is warmed by the Sun, but the outer region is cold enough to form ice on grain surfaces. The envelope consists of gas that has fallen in from the surrounding dense cloud. A bi-conical cavity has been cleared out by a wind.

young planetesimals, altering their thermo-mechanical evolution and outgassing volatiles (e.g., Lichtenberg *et al.* 2016). Extrasolar planetesimals without ^{26}Al would have more ice because of this lack of heating, and they would deliver perhaps 10 times more water to their terrestrial planets (Ciesla *et al.* 2015, Lichtenberg *et al.* 2019). The risk of producing water planets (planets with massive, deep water oceans) would be much higher, and such planets are probably much less conducive to forming life. The formation of terrestrial life seems to profit from the availability of surface where water and land meet.

3. Proto-planetary Disks

Figure 3 shows a schematic view of the formation of a low-mass proto-planetary disk like the one that might have formed the Earth. The young star in the center is shown with a small cleared cavity around it (e.g., Andrews *et al.* 2016), and this is surrounded by a disk with an increasing thickness that channels a polar outflow on both sides (for observations of disk outflows, see the discussion by Per Bjerkeli in this volume.). Towards the edge of the disk, the centrifugal force balance for inner circular orbits changes into a more radial force balance between accretion ram pressure and thermal disk gas pressure. The edge of the disk is also heated by this accretion. The figure shows the demarcation between an inner warm part, heated by the star, and a cooler middle part where water ice and snow can form on grain surfaces. Essentially all of these features have been observed, including the snow line (see Symposium reviews by Laura Pérez and Inga Kamp and a discussion of the inner parts of disks around low mass stars by Jozsef Varga). Curiously, the Earth is positioned too close to the Sun to lie within the snow region, making the origin of the Earth's water more indirect. The contribution by Germán Chaparro Molano *et al.* to this Symposium illustrates the many possible types of planetary systems and planet distributions that can come from disk evolution. The complex chemistry of disks and their envelopes is discussed in this volume by Yoko Oya, while disk MHD simulations are discussed by Mario Flock. The effect of stellar flares on disk chemistry is considered in the contribution by Peter Abraham.

Proto-planetary disks are also magnetic. Figure 4 shows the magnetic field morphology of a young stellar object from the observations by Alves *et al.* (2018). The field orientation is shaped by the flow direction, as indicated by the shades of velocity. The magnetic field

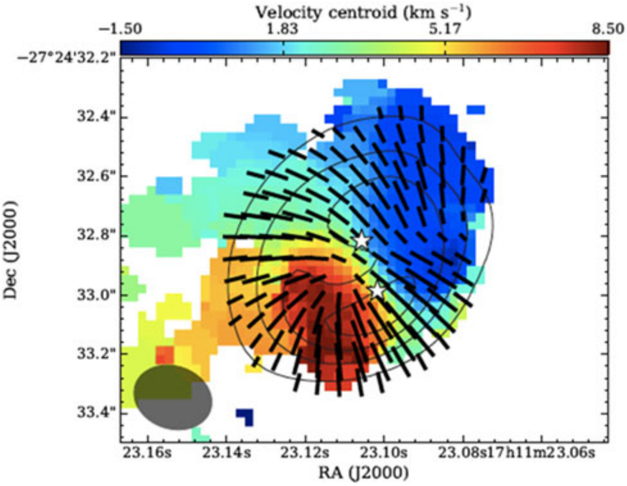

Figure 4. Velocity and magnetic field structure in the proto-solar nebula BHB01-11, from Alves *et al.* (2018). The lines showing the magnetic field orientation are from polarization emission in the far-infrared, rotated by 90°. The velocities are from H_2CO emission and the contours are from Stokes I emission.

morphology can be inferred from the polarized emission of elongated dust grains aligned perpendicular to the magnetic field lines. Dust self-scattering and radiative alignment also produce polarized emission (e.g., Kataoka *et al.* 2017). Azimuthal magnetic fields can stabilize a disk against gravitational instabilities that could form planets (Lizano *et al.* 2010). Observations reported by Anaëlle Maury in this volume suggest an increased importance for magnetic fields from the apparent small sizes of Class 0 protostars.

4. Planetesimal Formation

The heavy elements in a cosmic mixture generally condense into micron-size grains or smaller, and this is the form they most likely had when they entered the solar system along with the gas in a collapsing interstellar cloud. In the high density of the pre-solar nebula, the grains can stick together and accumulate into larger objects, which through a series of collisions and fragmentations, ultimately make rocky or icy planetesimals. Continued collisions combined with ever increasing gravitational forces eventually make the rocky planets like Earth, and for stronger gravity, the larger planets like Jupiter (see the Symposium review by Eiichiro Kokubo, and the discussions in this volume by Francesco Pignatale about the early stages of chondrite formation, and Sergei Ipatov about the formation of the moon). These grain collisions are aided, in part, by their differential drift through the gas, which is caused by a slightly slower orbital velocity of the gas component in the presence of a radial pressure gradient (Weidenschilling 1977). The grains do not feel this full pressure gradient; their attempt to orbit at Kepler speed meets with a headwind, breaking their orbital motion differentially with regard to size so that relative velocities build up and therefore collisions between particles become frequent.

Figure 5 shows how grain-grain interactions depend on their size (from Windmark *et al.* 2012). The tiniest grains can stick together (region “S” in the figure) when they collide, but millimeter and centimeter size grains can stick and bounce (“SB”) or bounce (“B”) off each other, or transfer mass (“MT”) and erode (“E”) the largest of the pair. Large equal-size grains can fragment (“F”) when they collide. While the fragmentation regime for similarly sized bodies counteracts planetary growth, the “bouncing barrier” (in yellow)

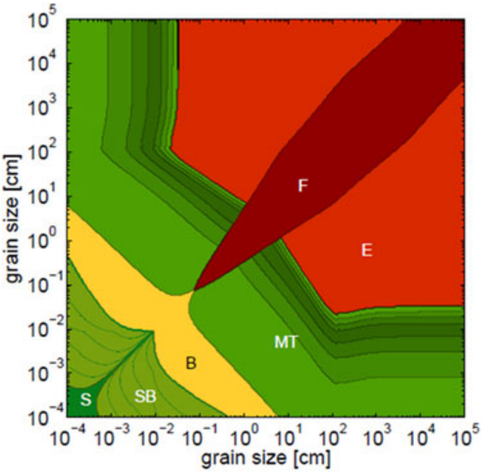

Figure 5. The outcomes of collisions between solid particles are shown by the various shadings in this diagram, as a function of the particle sizes. The letters represent collisions that are sticking (S), stick and bounce (SB), bounce (B), mass transfer (MT), erosion (E), and fragmentation (F), from Windmark *et al.* (2012). The relative velocities between the particles are from a distribution with four sources of grain drift: Brownian motion, turbulence, azimuthal drift and radial drift.

keeps most of the particles small; if only a few bodies cross the barrier by some exceptional conditions, then they can efficiently grow by sweeping up the large number of small bodies without being rapidly fragmented.

The resulting planetesimals that form in icy regions may look like the icy surfaces of comets. Comets that have been photographed by space missions have complex chemical compositions and inhomogeneous surfaces, with important chemicals for life, like water, phosphorus, amino acids and other organics (Altwegg *et al.* 2016).

5. Molecular Emission from Disks

A variety of ring morphologies are found in molecular emission line observations of proto-planetary disks. Ices on grain surfaces tend to occur beyond a certain radius where the temperature is low. There are several ways to probe these snow lines. CO is usually too optically thick, frozen out on dust, or depleted for some other reason to see its full density structure, but its presence and the transition from gaseous CO to frozen CO can be inferred indirectly using N_2H^+ observations. N_2H^+ is destroyed by chemical reactions with CO in the gas phase, so a sudden transition to N_2H^+ emission at some radius could mean the presence of gaseous CO inside that point and frozen CO outside. TW Hya is an example: N_2H^+ is observed only outside a certain radius; that boundary, at a few tens of AU, should be the CO snow line (Qi *et al.* 2013). This radius is large enough to be spatially resolved with ALMA observations. The water snow line is generally much farther in and difficult to resolve in typical disks. When a disk experiences a burst of accretion, however, as in FU Ori type stars, the water snow line extends outwards because of the surge in disk temperature. Around the FU Ori star V883 Ori, Cieza *et al.* (2016) found an abrupt change in dust brightness at 40 AU, which may be caused by dust fragmentation and an increased dust surface area inside the temporary water snow line. Emission of CH_3OH, which has a similar volatility to water, is indeed detected around this transition radius (Lee *et al.* 2019).

There are many ALMA images of dust continuum emission from proto-planetary disks (see review by Laura Pérez in this volume). For planet formation, we also need to know the distribution of the gas, which is the major component in the disk (see reviews by Inga

Kamp and Xuening Bai in this volume). The gas/dust ratio is crucial for some theories of the formation of Jupiter-type planets, which rely on gravitational instabilities or gravity-driven waves (Lichtenberg & Schleicher 2015). The gas/dust ratio is also important for radial migration of dust particles and protoplanets in the disk. Since H_2 is hard to observe, CO and other molecular lines are used as tracers of disk gas. CO depletion by sedimentation of ice-coated dust grains and chemical conversion to other species is a critical issue in the estimation of the gas/dust ratio. H_2O can also be photodissociated to be converted to other molecules. Thus the emission by molecules and the inference of disk properties depends on the interaction between the disk and the stellar UV and ionization by X-rays and decaying ^{26}Al.

While simple molecules such as CO and CN have long been detected in disks, detection of larger molecules became possible only recently thanks to ALMA (see the paper in this Symposium by Jes Jørgensen *et al.*). For example, CH_3OH, CH_3CN and HCOOH have been detected in TW Hya (e.g., Loomis *et al.* 2018). The excitation temperature of CH_3CN is several tens of Kelvin, which indicates that these molecules are non-thermally desorbed from ice. The detection suggests that exoplanet systems could be rich in organics, as was our Solar system (Nakamura-Messinger *et al.* 2006, Altwegg *et al.* 2016). Quantitative comparisons of their abundances with those in comets are of special interest, but not straightforward.

An important question is how the Earth got its water. As mentioned above, the Earth probably formed in a water-dry zone because of its close proximity to the Sun, while water-rich planetesimals formed further out where the temperature was lower. These outer planetesimals could have reached the Earth during a large-scale radial migration of the giant planets, which would have scattered the smaller objects all around (Walsh 2011). In such models, Jupiter-like planets could have had an important role in the origin of life on Earth by indirectly delivering water. The contribution by Mikhail Marov to this volume discusses more about the delivery of water to Earth.

Doris Breuer in this Symposium discusses how water could have come to Earth in two forms: hydrated solids that built up the interior and degassed through volcanic action to supplement the atmosphere, and volatile-rich comets and asteroids that deposit their water directly into the atmosphere, oceans, or surface layers. Plate tectonics on the Earth could have an additional effect on moving water both into and out of the mantle, establishing an equilibrium in surface water content. Planets like Mars without plate tectonics could be continuously losing their water.

6. Gaseous Envelopes around a Young Earth

A young Earth-size planet can accrete a massive H+He envelope from the gas surrounding it in the disk. Because the gaseous part of a protoplanetary nebula is 100 times the mass of the rocky, dusty part, this envelope may contain several Earth-masses of gas, depending on how massive the planetary core grows in the disk. If such an envelope formed and could not be dispersed, then the Earth would be more like a mini-Neptune today. These are not atmospheres in the conventional sense of terrestrial planets. Their surface pressures are huge, and their temperatures high, not supporting habitable conditions. This could be true even for an Earth-like planet in the so-called habitable zone of its star, because that zone is usually defined for planets that contain only light atmospheres like the present-day Earth, Venus or Mars.

There are two solutions to this problem: *First,* the Earth-like planet could form very late, after the nebular gas is gone. One way to limit the lifetime of the proto-planetary disk itself and therefore limit envelope accretion is to remove the gas in a disk is through irradiation by stellar X-rays and/or extreme ultraviolet, which can heat the disk and evaporate it (Alexander *et al.* 2006, Ercolano *et al.* 2008). Once the gas disk is removed, the envelope around a terrestrial planet feels less confining pressure and can expand. According to Stökl *et al.* (2015), low mass terrestrial planets can lose a significant fraction of their envelopes, but high mass planets including those with about an Earth mass, cannot.

Second, if an envelope has already built up when the gas disk disperses, then the irradiation of the envelope by strong stellar X-ray and extreme-ultraviolet (XUV) radiation can heat and progressively evaporate the upper layers of the envelope until it may completely disperse. Under typical circumstances, if the planet avoids accreting up to about one Earth mass already during the disk lifetime of a few million years, its envelope remains thin enough to escape rapidly. If the planet does accrete about two or more Earth masses, it inevitably evolves into a mini-Neptune that will never lose its envelope during the main-sequence life of the host star (Lammer *et al.* 2014.) We see here that a delicate balance between timescales of disk dispersal, planetary solid accretion and stellar activity is crucial for the fate of planetary habitability. Further discussion of atmospheric escape from young planets is in the contribution to this volume by Valery Shematovich and Dmitry Bisikalo. Atmospheric models of habitable planets are in the discussion by Nicolas Iro.

7. Stellar Activity

While the Earth was slowly forming in the proto-solar nebula, the Sun was forming also. Observations of young stars like the Sun show them to be highly active with typically fast rotation, strong variability and a high X-ray flux from flares and other energetic processes (see the discussions in this volume by Orsoly Fehér and John Pye). Based on these observations, we infer that the young Sun had a faster rotation rate than today, and more dynamo action with a stronger magnetic field as a result. A strong magnetic wind then caused the Sun to spin down and lose its high level of XUV and wind activity.

A magnetized wind has so far only been detected from the Sun (the Solar Wind), but the evidence for stellar magnetized winds is the systematic lengthening of the rotation periods of solar and lower mass stars over a half Gyr timescale (Gallet & Bouvier 2015, Johnstone *et al.* 2015). This spin-down is, however, not unique - it in fact depends on the initial rotation period of the star after the proto-planetary disk dispersed. After initial spin-up due to continuing stellar contraction, the star spins down due to angular momentum removal by the wind, but this spin-down is slow if the star started out as a slow rotator, and it is fast if it initially rotated rapidly (up to a hundred times the present solar rotation rate), as both observations of stellar samples and theoretical wind models confirm (Johnstone *et al.* 2015). While this spin-down behavior leads to nearly the same rotation rate after a billion years no matter what the initial rotation rate was, it is interesting that in the time range between around ten and a few hundred Myr stars can take widely differing evolutionary paths with corresponding XUV levels differing by factors of 20 to 40 between fast and slow rotators (Figure 6). By pure accident, this coincides with the time period in which the Earth formed a crust and liquid ocean and presumably outgassed its secondary atmosphere. Such stellar variation is therefore crucial for removing H/He envelopes, but it is also crucial regarding terrestrial-type secondary (outgassed) atmospheres. Too much high-energy irradiation may remove secondary atmospheres, but too low irradiation levels may fail to remove primordial H/He envelopes. Another delicate balance thus becomes evident for the development of habitable conditions, namely between H/He envelope removal and the subsequent preservation of a secondary atmosphere. The main stellar parameter that determines the outcome of this balance is the stellar initial rotation rate, for which nature offers a spread of about two orders of magnitude and therefore a variety of planetary outcomes for any given primordial H/He

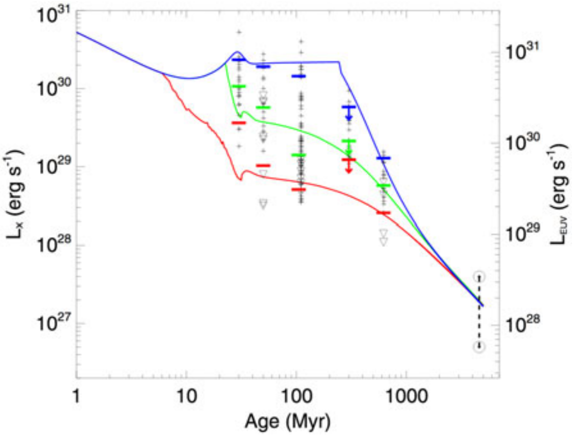

Figure 6. Predicted evolution of L_X (left y axis) and corresponding $L_{\rm EUV}$ (right axis) for three initial rotation rates for a solar-mass star, evolved using a rotation-wind-angular momentum evolution model (Johnstone *et al.* 2015). The blue, green and red curves show the evolutionary tracks for an initially fast, medium, and slow rotator, respectively, for the 10th, 50th, and 90th percentiles of the rotation rate distribution in very young clusters. The individual + symbols are observed values in co-eval cluster samples, inverted triangles mark upper limits. The solid horizontal bars show the 10th, 50th, and 90th percentiles of the observed distributions of L_X at each age. The two solar symbols at 4.5 Gyr show the range of L_X for the Sun over the course of the solar cycle (from Tu *et al.* 2015).

envelope and outgassed atmosphere. Some combinations may lead to habitable conditions, while many may not. More on this topic is in the Symposium contribution by Theresa Lüftinger.

Smaller planets like Mars may lose their atmospheres completely due to stellar activity because their gravity is small. Erkarv *et al.* (2014) showed that Mars should have lost both its H/He envelope and its outgassed H_2O and CO_2 atmospheres in about 10 Myr, with the possibility that its current atmosphere outgassed or was delivered by impacts later.

In summary, these considerations suggest that long-term habitability depends on more than the possibility of liquid water under an Earth-like atmosphere. It requires that the H and He-rich primordial envelope around the planet be removed by solar activity (or that the planet forms very late, after the nearby nebular gas has been removed), and that the planet have enough mass (bigger than Mars) to resist complete solar removal of its atmosphere and be far enough away from the early Sun (further than Venus) to avoid getting too hot.

The long-term evolution of the central star is important, too. The Sun was bolometrically about 10 times brighter when it formed than it is now, and its bolometric luminosity dropped by a factor of $\sim$100 in the first 10 Myr. It gradually increased in the next 30 Myr and then, as terrestrial planets accreted to their final mass, stabilized to about a constant output over the remaining 4 Gyr. In another 4 Gyr the Sun's luminosity will increase back up by a factor of about 10 as it turns into a red giant.

Stars with non-solar masses may not have such a favorably long time with a near-constant luminosity. Solar-type stars are ideal as they settle quickly to a steady brightness while the planets are forming and then remain fairly constant for several Gyr, starting with the era when the Earth acquired a habitable, water-rich surface and atmosphere, and sophisticated life formed and developed. More massive stars evolve more quickly at first but burn out sooner. Lower-mass stars settle to their stable states much more slowly.

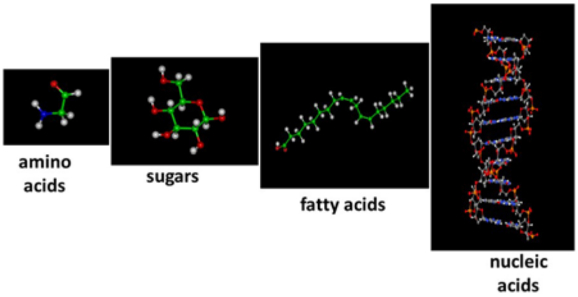

Figure 7. Complex molecules that are the building blocks of life, from the contribution to this volume by Addy Pross.

An M1-type star with about half the mass of the Sun takes ∼ 100 Myr before its luminosity stabilizes; before this time, the luminosity drops by a factor of ∼ 10 as a power law with time. The situation becomes progressively more serious for later-type M dwarfs, the latest ones declining by a factor of ∼ 100 in bolometric luminosity over at least one Gyr. In a case like this, a planet orbiting it at a certain radius may be inside the habitable zone at first, baking in an early hot phase and losing its oceans and atmosphere. The habitable zone then shrinks as the luminosity decreases, passing though the planet's orbit until it lies inside, at which point the planet may be too cold for liquid water (see, e.g., Ramirez & Kaltenegger 2014). Further discussions of the effects of stellar flares on habitability are in the contribution by Adriana Valio in this volume, while Ximena Abrevaya reports experiments on biological reactions to UV radiation.

8. Constraints from Orbital Dynamics

How important are the outer planets for Life on Earth? They seem to be quite important. Pilat-Lohinger *et al.* (2008) and Pilat-Lohinger (2015) considered orbital perturbations affecting the Earth's eccentricity from the outer planets Jupiter and Saturn. They show that if Saturn had ended up at 8.7 au instead of 9.5 au, the eccentricity of the Earth would vary periodically over a few Myr timescale, reaching maximum eccentricities of 0.6–0.7. Then the Earth at perihelion would bake with an equatorial land surface temperature of 80 C, while the Earth at aphelion would freeze with a temperature of near 0 C even at the equator (Williams & Pollard 2002). Stability of the Earth seems to be a key factor in the development of life, and both the central star and the other planets can have a strong influence on that. The implications of planet spin-orbit locking to habitability is discussed in the contribution by Amri Wandel. Observations of Earth-like planets are reviewed by Daniel Apai.

9. Origin of Life

What defines the transition from chemistry to biology? Some life forms such as the cyanobacteria have existed on Earth nearly unchanged in morphology for several billion years. Where did the first biomolecules come from? The amino acids, sugars, fatty acids, and nucleic acids shown in Figure 7 are not life and yet they make up living things. Lipids make vesicles, amino acids make peptides and proteins, nucleotides make RNA and DNA. The basic ingredients of these complex structures are molecules commonly found in interstellar space, H_2, CO, CH_4, NH_3, N_2, HCHO, HCN.

The big unknown is how relatively simple molecular systems with hundreds of atoms assembled into complex biological systems with trillions of atoms, in apparent contradiction to the second law of thermodynamics, which tends to mess things up. To quote

Erwin Schrödinger (1944): “we must be prepared to find it (living matter) working in a manner that cannot be reduced to the ordinary laws of physics.”

A general rule governing change in both physical and biological worlds is that unchanging things do not change and changing things do change until they change into things that do not change. Nature may have used this logical principle to make persistent forms of life, with replication the key physical process (Pascal & Pross 2015, Pascal & Pross 2019).

Two evolutionary paths toward persistence are described in the Symposium review by Addy Pross. In the “Regular World”, random processes reach thermodynamic equilibrium, and the relevant mathematics is Boltzmann statistical mechanics. In particular, the log of the number of states in a system, which is proportional to the entropy, always increases with time. In the “Replicative World”, however, multiplicative processes cause exponential growth. Then the relevant mathematics is Maltusian growth governed by terms involving the sources (replication) and sinks (death) of particular structures. The basic equation for the Replicative World is

$$dX/dt = kXM - gX, \tag{9.1}$$

where population concentration X replicates in proportion to the concentration of resources, i.e., building blocks, M, and the rate, k, and decreases in proportional to a destruction rate, g. When $kM > g$, the growth is exponential until the resources, M, get depleted and $kM = g$, as which point the population reaches equilibrium. Pross calls this “Dynamic Kinetic Stability.”

Examples of structures in thermodynamic stability in the Regular World are the chalk cliffs around Dover, UK. They have stability and persistence for 60-100 Myr through a lack of chemical reactivity. Examples of Dynamic Kinetic Stability in the Replicator World are ants, which have persisted for 140-160 Myr, and cyanobacteria, which have persisted for 2000-3000 Myr. Their stability comes from bounded self-replication.

There is no clear evidence for life outside the Earth at the present time. Eduardo Janot Pacheco in this volume considers possible signatures in molecular emission lines for what might be pieces of DNA in interstellar clouds. Possible signs for life on the water-moon Enceladus were discussed by Ruth-Sophie Taubner.

10. Conclusions

There is a sequence of events that have to go right for the formation of life on an Earth-like planet. There has to be a star-formation environment that can make a solar mass star, possibly even with ^{26}Al production if that turns out to be necessary to help melt planetesimals and control the delivery of water. The collapse of the interstellar cloud may need to bring in certain molecules too, such as water, if these molecules cannot be made in the required abundance in the protosolar disk itself (Cleeves *et al.* 2014). Disk chemistry and gas-grain reactions need to put water and other important molecules for life in a usable form, such as in ices on grain surfaces that can be transported to rocky planets. Other organics may need to form in the nebular disk as well. The disk grains then have to grow into planetesimals and eventually Earth-size rocky bodies, which need a light atmosphere to avoid over-heating by the greenhouse effect. This latter step requires either the removal of a massive gaseous envelope of nebular H and He by energetic processes from the young Sun, or a delayed formation of the Earth to a time when there is no local nebular gas. How stellar energetic processes evolve and erode planetary atmospheres depends primarily on the initial stellar rotation period, which in turn is determined by accretion and protostellar disk evolution and dispersal. Water ice and other ices from the cooler regions of the disk, possibly accompanied by organic molecules, have to scatter into the Earth’s orbit and eventually to the Earth’s surface. Soon after this, the Sun has to be relatively stable for a long time, without large luminosity fluctuations that could throw the Earth into boiling or freezing conditions or destroy its atmosphere.

There could be other environments and pathways to life too, such as through chemical reactions at the rocky bottoms of oceans that are frozen over on the surface. Perhaps some of this diversity can be tested in our own Solar System.

Evidently, life is a product of astrophysical diversity. Astrophysical initial conditions and boundary conditions of protostellar collapse, disk evolution and initial stellar mass and angular momentum as well as planetary properties such as growth rate, final mass and outgassing rate offer many planetary pathways. Apart from initial conditions, the timing of a series of successive events in the star-planet environment and in the planet itself must be right, and timescales matter to fulfil critical conditions for the evolution toward a habitable surface environment. Many pathways will fail to produce habitable conditions even at the "right distance" from the host star because various timescales are "wrong", but some combinations will succeed, as our solar system amply proves.

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