ASTRO-BIOLOGICAL SIGNATURES
Prospects for the detection of non-terrestrial biological material

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Abstract: The possibilities for detecting non-terrestrial biological material are briefly reviewed in light of the flurry of extrasolar planet detections over the last ten years and the forthcoming space missions designed to search for signs of extraterrestrial life. We summarize the evidence for non-terrestrial organic material and the challenges involved in the development of robust and reliable biosignatures, i.e. features whose presence requires a biological origin. It is necessary to distinguish between prebiotic material, which is likely to be a necessary precursor to life but which is not produced by a biological system, and the detection of either biological material itself or its effect on the environment. We discuss the use of chirality and spectrally resolved circular polarization as a remote-sensing technique for distinguishing between biological and non-biological substances.

Key words: Astro-biology, chirality, circular polarization

1.   INTRODUCTION

The detection of non-terrestrial biological material is complicated by the lack of a strict definition of what is meant by "biological." However, we do know that life on Earth has a carbon-based organic chemistry, requiring liquid water as a solvent to mediate reactions, and so it is reasonable to search for evidence of similar systems elsewhere. Although other biochemistries have been suggested, there are good reasons to suppose that a carbon/water-based biochemistry may be universal (Chyba & Hand 2005).

Carbon is a by-product of stellar evolution and is returned to the Galaxy in huge quantities in the winds of giant stars. To date, almost 100 species of carbon-based organic molecules have been detected in a range of astrophysical environments, from nearby star-forming clouds to distant galaxies (Ehrenfreund *et al*. 2002), suggesting that the building blocks of life are widely available.

Studies of chondritic meteorites, dating from the earliest phases of the solar system, show evidence for complex organics including amino-acids (e.g. Cronin *et al*. 1981). This material will have been delivered to the early Earth, as well as to other planets, potentially kick-starting the biological process at more than one site in the solar system. Although Mars appears largely desiccated today (however see Murray *et al*. 2005 for recent evidence of a frozen sea close to Mars' equator), there is abundant evidence that surface water has existed there in the geologically recent past (Baker 2001), raising the possibility that microbial life may have existed at some point. Another site of considerable interest from a biological point of view is Europa, a moon of Jupiter, which is thought to possess an ocean of liquid water below its icy surface (Carr *et al*. 1998; Kivelson *et al*. 2000).

The tenacity of life and its ability to flourish in extreme environments, often without access to solar radiation, is demonstrated by communities of extremophile microorganisms on Earth (Rothschild & Mancinelli 2001). Many of these extremophiles have been found to belong to an ancient branch of life, dubbed "Archaea," which have fundamental similarities to higher organisms (Woese 1987). Extremophilic microorganisms have been found in some of the harshest environments, such as in hydrothermal vents above 100 $^{\circ}$C, frozen ice cores, permanently saturated sodium chloride lakes, and highly acidic and alkaline waters, greatly expanding our definition of the habitable zone on our planet. Notable examples include the large extremophile populations discovered in deep anoxic basins (van der Wielen *et al*. 2005) and in sub-seafloor sediments (Schippers *et al*. 2005).

Techniques for detecting biological material are especially important at a time when space missions are currently investigating the most likely sites for life elsewhere in the solar system. The STARDUST mission, to capture cometary material for analysis, returned safely to Earth in January 2006 after an encounter with comet Wild 2. It is also only ten years ago that the first detection was made of an extrasolar planet orbiting a main sequence star (Mayor & Queloz 1995), opening up the field of extrasolar planetary research. Within the next few years, with the launch of new planet-finding space missions, such as KEPLER (Borucki *et al*. 1996) and COROT (Deleuil *et al*. 1996), we will have, for the first time in our history, a good idea of the number of Earth-like planets (ELPs) in our Galaxy. These ELPs will then be investigated by the Terrestrial Planet Finder (NASA) and Darwin (ESA)

space missions, due for launch in the next decade, which are intended to search directly for evidence of habitability and the presence of life.

2.   PREBIOTIC MATERIAL

Spectral-line studies of circumstellar environments have identified many complex organic molecules (Friedel *et al*. 2005, Ehrenfreund *et al*. 2002, White 2004). The detection of glycolaldehyde (Hollis *et al*. 2000; Halfen *et al*. 2006) is of particular biological significance, since it is the simplest monosaccharide sugar and may be a key stage in the formation of ribose. Acetic acid, which may be involved in the synthesis of glycine, the simplest amino acid, has been detected towards Sgr B2 (Mehringer *et al*. 1997). Searches for interstellar glycine in the gas phase have so far been inconclusive. Kuan *et al*. (2003a) reported a tentative detection of glycine towards three hot molecular cloud cores, but this has since been disputed by Snyder *et al*. (2005). Attempts to detect other prebiotic materials, such as pyrimidine (a component of nucleic acids) in the interstellar medium (ISM) have also so far proved to be unsuccessful (Kuan *et al*. 2003b).

The largest carbon molecules in the ISM are likely to be polycylic aromatic hydrocarbons (PAHs), which are thought to be responsible for a range of infrared interstellar emission features (Léger & Puget 1984). The various emission features (principally at 3.3, 6.2, 7.7, 8.6 and 11.2 μm) are due to stretching and bending modes of the C-C and C-H bonds, although there has not been, as yet, a conclusive identification of a specific PAH with an astronomical spectral feature. In an attempt to fit the 6.2 μm interstellar emission band, Hudgins *et al*. (2005) conclude that PAHs with a nitrogen atom substituted into the structure are required, forming endoskeletal PANHs (polycyclic aromatic nitrogen heterocycles). Although PAHs do not play a role in terrestrial biology, PANHs are possible precursors of a prebiotic chemistry and bear some similarities with biologically important molecules, such as chlorophyll.

Most complex organic molecules are expected to form more readily on the surface of dust grains, rather than in the gas-phase ISM. UV photolysis of interstellar ice analogues in the laboratory, under conditions that are thought to be typical of the molecular cloud from which the solar system condensed, has been shown to produce amino acids such as glycine, alanine and serine, after hydrolysis (Bernstein *et al*. 2002). Muñoz Caro *et al*. (2002) identify 16 amino acids in their UV-irradiated ice residue. In both cases, the chiral amino acids appear to be racemic (equal numbers of the left and right handed enantiomers are produced). Prebiotic molecules produced in the solar nebula will have been incorporated into primitive solar system bodies such

as comets and asteroids and may have been delivered to the early Earth during the heavy bombardment phase (Chyba *et al*. 1990). Direct evidence for this process is provided by the detection of indigenous amino acids in the Murchison meteorite, a carbonaceous chondrite that fell to Earth in 1969 (Kvenvolden *et al*. 1970). More than 70 amino acids have been identified in Murchison, over 50 of which are not involved in biology on Earth. Although the initial analysis suggested a small excess of L-enantiomers, which was attributed to terrestrial contamination, Engel & Nagy (1982) reported a larger L-enantiomer excess for several amino acids, for which they claimed an extraterrestrial origin. This has been disputed by Bada *et al*. (1983), who attributed the result to contamination, as in the original study. To avoid the contamination issue, Cronin & Pizzarello (1997) analyzed 4 of the non-terrestrial amino acids and again detected an L-enantiomer excess, of between 7.0 and 9.1 per cent, concluding that, at least in the case of some of the Murchison amino acids, the L-excess must be indigenous to the meteorite. The issue is an important one, since it is unclear whether the origin of homochirality in terrestrial biology (with nearly all amino acids being L-enantiomers and sugars D-enantiomers) predates life, or is a consequence of it.
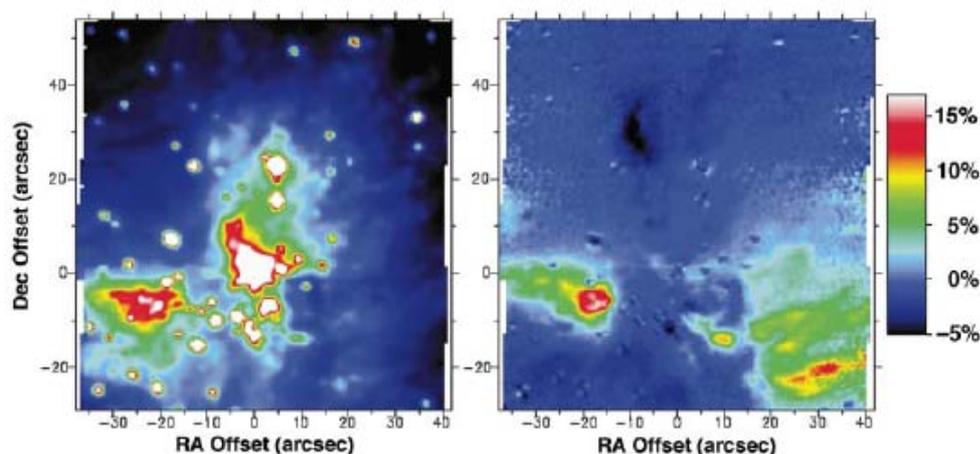

Figure 1. Circular polarization image of the OMC-1 star-forming region in Orion at 2.2 μm, from Bailey *et al*. (1998). Total intensity is shown on the left with the bright Becklin-Neugebauer (BN) object at coordinate (0,0). Percentage circular polarization is shown on the right, ranging from -5% (black) to +17% (white). A region of high (up to 17%) circular polarization is seen to the west of the BN object at coordinates (-20, -7).

It has been shown in the laboratory that irradiation of racemic substances with circularly polarized light can result in enantiomeric excesses (Bonner

1991). A mechanism for UV photolysis by circularly polarized light in star-forming regions was proposed by Bailey *et al*. (1998), following their discovery of high degrees of circular polarization (up to 17% at 2.2 μm) in Orion (see Fig. 1). They argued that this could account for the chiral asymmetry of the amino acids in the Murchison meteorite, as well as explaining the origin of homochirality in terrestrial biological molecules. If enantiomeric excess can be produced abiotically in this way, then the usefulness of chirality as a biosignature may be complicated (Section 5).

3. EXTRASOLAR PLANETS

The prime motivation for the development of remote-sensing techniques, designed to identify biosignatures, is provided by the discovery of more than 170 extrasolar planets during the last 10 years (see Marcy *et al*. 2005 for a review). To date, nearly all of these detections have been made indirectly using the radial velocity technique, which measures the Doppler shift in the spectral lines of the star as it orbits about the gravitational centre of the star-planet system. The magnitude of the effect depends upon the orientation of the planet's orbit relative to our line of sight, and so the apparent mass, $M\sin i$, is measured, where i is the inclination angle and M the actual planetary mass.

Most of the discovered planets are gas giants, with $M\sin i$ in the range 0.1 to 13 Jupiter masses (1 Jupiter mass is equivalent to 318 Earth masses), orbiting close to their parent stars. As the precision of the Doppler radial velocity technique has improved, this mass limit has been pushed down, and a number of Neptune-mass planets ($M\sin i$ in the range 14 to 21 Earth masses) are now known (Santos *et al*. 2004; Butler *et al* 2004; McArthur *et al*. 2004). More recently, the first likely "super-Earth" has been detected, orbiting a nearby (4.7 pc) star (Rivera *et al*. 2005). This planet is part of a multiple system already known to contain other Jupiter-mass planets, and by making assumptions regarding the coplanarity of the orbits, Rivera *et al*. determine a mass of 7.5 Earth-masses. The mass distribution of the planets detected so far can be approximated by an inverse power law, $dN/dM \propto M^{-1.05}$ (Marcy *et al*. 2005), which rises steeply toward the lower mass limit, suggesting that there may be a potentially large number of Earth-mass planets awaiting discovery. This possibility is further supported by the very recent report of a 5.5 Earth-mass planet orbiting a cool M-dwarf star, discovered through gravitational microlensing (Beaulieu *et al*. 2006).

The radial velocity technique is unlikely to be able to detect Earth-mass planets around solar-type stars. The Doppler precision required to detect an Earth orbiting at 1 au around a solar-mass star is 3 cm s^{-1} (Tarter 2001);

whereas, limitations due to line broadening in the stellar spectrum are likely to restrict accuracy to not much below 1 m s^{-1}. Gravitational microlensing surveys, on the other hand, are well-suited to detecting Earth-mass planets with orbital radii between 1 and 5 au. Statistically, however, planets discovered using this technique are likely to be much too distant to follow up with direct detections (the recent discovery by Beaulieu *et al*. (2006) lies at a distance of 6.6 kpc). An alternative technique is to use precision astrometry to measure the stellar wobble due to an unseen orbiting planet. The ESA GAIA mission, due for launch in 2011, should be capable of discovering thousands of planets around nearby main sequence stars (Perryman *et al*. 2001). The SIM Planetquest mission, scheduled for launch next decade, is expected to be capable of detecting planets with mass greater than 3 Earth-masses orbiting between 0.1 and 2 au around nearby (<20 pc) stars (Marcy *et al*. 2005). This range of orbital radii is important for the future detection of ELPs, since it encompasses the habitable zone (HZ) for solar-type stars, the region around the star in which life-supporting planets might exist. The HZ is usually defined by the requirement that liquid water should exist on the planet's surface and, for our own solar system, a conservative estimate of its width is from 0.95 au to 1.37 au (Kasting *et al*. 1993). For cooler K and M spectral-type stars, the HZ occurs further in and is narrower. For hotter F type stars, it occurs further out and is wider. In a study of the development of photosynthesis, Wolstencroft & Raven (2002a) conclude that an F0V star provides the best environment for an ELP. Stars hotter than F0 will have main sequence lifetimes less than 2 Gy and so these systems may be less favourable to the evolution of life.

For planets orbiting in a plane close to our line of sight to the star, there is a possibility that the planet will transit the star, causing an occultation. The first transiting extrasolar planet was discovered in 2000 (Henry *et al*. 2000, Charbonneau *et al*. 2000, Mazeh *et al*. 2000) around the star HD209458, and a total of 7 are known so far, 5 of which were discovered using their transits. As well as providing information on the orbit, mass and radius of the planet, transits can also allow the planetary atmosphere to be studied, as the background stellar light is transmitted through it. In the case of the planet around HD209458, several transits have been observed and absorption lines attributable to atomic sodium and hydrogen have been detected, probing both the lower and upper atmosphere (Charbonneau *et al*. 2002; Vidal-Madjar *et al*. 2003). Most recently both carbon and oxygen have been detected in the upper atmosphere (Vidal-Madjar *et al*. 2004), the first detection of these biologically important elements in an extrasolar planet atmosphere. However, HD209458b is not an ELP but rather a gas giant, orbiting extremely close to its star (within 8.5 stellar radii). The hot, extended atmosphere is in the process of being evaporated. Recently,

Deming *et al*. (2005), using Spitzer observations, report the detection of mid-infrared radiation from HD209458b, by observing the reduction in flux during secondary eclipse, when the planet passes behind the star.

4. POTENTIAL BIOSIGNATURES

A major goal of the TPF (Beichman *et al*. 1999) and Darwin (Léger *et al*. 1996) missions is to search for habitable planets around a large number of nearby solar-type stars and to detect spectroscopic evidence for life. The first objective involves determination of the orbital and physical properties of the planet to assess habitability. If the planet is located within the star's HZ, with a modest orbital eccentricity, then liquid water can exist at the surface. In order to maintain a constant surface temperature over long periods, however, it is likely that a climate stabilization mechanism similar to the carbon-silicate weathering cycle on Earth will be necessary. This negative feedback loop is capable of reversing periods of global glaciation as well as preventing a runaway H_2O greenhouse (e.g. Kasting & Catling 2003) and would have been particularly important in early Earth history when the Sun was less luminous than today. The process requires long-term tectonic activity so that it is likely that any ELP will be volcanically active, meaning that planetary mass is important. The lack of long-term volcanic activity on Mars, due to its small mass (one ninth that of Earth) and short cooling timescale, probably contributed to the loss of its atmosphere. The second objective, for the spectroscopic detection of life, necessitates the establishment of reliable biosignatures.

4.1 Atmospheric Biosignatures

The detection of an atmospheric biosignature would provide indirect evidence for life, as long as non-biological processes can be ruled out. The best candidate is usually considered to be O_2, and its photolytic product O_3. Although O_2 can be produced non-biologically by the photodissociation of water, this is not likely to be a long-term source unless the planet is in a runaway greenhouse phase, when all of the water may be evaporated into the atmosphere. This situation is thought to have led to complete water loss on Venus and defines the inner edge of the HZ. However, large amounts of atmospheric O_2 on an ELP with a reducing crust and surface temperature compatible with liquid water, may be a strong indicator of continuous production and, hence, biological (photosynthetic) activity. Léger *et al*. (1993) calculate that if photosynthetic production of O_2 were to cease on Earth, then O_2 would be removed from the atmosphere within $2 \cdot 10^7$ yrs.

Although O_2 has an absorption band at 760 nm, this would be difficult to observe unless the planet eclipsed the star. The contrast ratio between a solar-type star and an ELP varies from about 10^9 in the visible to 10^6 in the mid-infrared (Angel *et al.* 1986) so that observations of the O_3 absorption feature at 9.7 μm are likely to be more feasible. The photochemical production and destruction of O_3 are considered by Léger *et al.* (1993) and the process is non-linear. The relatively large O_3 column density at low O_2 partial pressures makes O_3 a potentially sensitive tracer of O_2; however, the non-linearity in the relationship means that it is difficult to determine the actual amount of O_2 present. The presence of O_3 in the atmosphere is in itself a necessity if surface dwelling organisms are to exist, since it provides an essential screen against the damaging effects of UV radiation. In marine environments on Earth, phytoplankton are significantly inhibited by solar radiation in the top 5-10 m or more of the water column (Herndl *et al.* 1993). In order to use light as an energy source, organisms need to be on the surface or in less than 300 m depth of water (Wolstencroft & Raven 2002a). A potential difficulty in using O_3 as a biosignature is that its detection may be complicated by the existence of other molecules with spectral features around 9.7 μm, such as NH_3, which absorbs in the 9-11 μm region, as seen in the spectra of Jupiter and Saturn (Léger *et al.* 1993).

Although the detection of large amounts of O_2 in the atmosphere of an ELP would be a strong indicator of oxygenic photosynthesis, and hence life, a non-detection would not prove the absence of life. Photosynthesis on Earth is thought to have evolved by at least 2.7 Gya, based on evidence for cyanobacteria in rocks from the Pilbarra (Brocks *et al.* 1999), but global oxygenation did not occur until 2.3 Gya, representing a 400 million year delay. Life may have formed long before the advent of photosynthesis, perhaps in the early Archean, approximately 3-3.5 Gya (Chyba & Hand 2005), although this is still controversial (e.g. Moorbath 2005). If so, then the Earth would not have had an O_2 biosignature for the first 0.7-1.2 Gy of its biological history. This has led some authors to consider biosignatures based on microbial ecosystems, thought to be characteristic of Earth's earliest biosphere (e.g. Pilcher 2003).

Other atmospheric gases, such as H_2O and CO_2, although not biosignatures, are important to biological systems. The presence of liquid water on a planet is considered to be a requirement for life; whereas, CO_2 is required for photosynthesis, and both have been designated as high priority observations for TPF/Darwin (des Marais *et al.* 2002). CO_2 has an absorption band at 15 μm and may be a good indicator of a terrestrial planet. A detection of methane (CH_4) on an ELP would be interesting, since it may have been the dominant greenhouse gas in the Archean atmosphere, when CO_2 concentrations are thought to have been low (Kasting & Catling 2003).

However, it can be produced both biologically, by methanogenic bacteria, and non-biologically in mid-ocean ridge systems, and so is ambiguous as a biosignature.

4.2   Surface Biosignatures

Whereas atmospheric biosignatures are indirect indicators of the presence of life, remote sensing of surface features may provide direct confirmation of extraterrestrial organisms. Such a feature could be provided by an abrupt change in reflectance of the planet's surface as a function of wavelength. The primary photosynthetic molecule, chlorophyll, has absorption peaks at 430 nm and 662 nm (chlorophyll A), giving vegetation its characteristic green colour. Between 700 and 1400 nm, green vegetation shows a large and abrupt increase in reflectance (from ~5% at 670 nm to ~70% at 800 nm) giving rise to a "red edge" in the reflectance spectra around 700 nm (e.g. Arnold *et al*. 2002). This red edge, due to vegetation, has been detected in observations of the Earthshine spectrum (see Fig. 2), which use the moon as a diffuse reflector by which to observe the integrated spectrum of the illuminated Earth (Arnold *et al*. 2002; Woolf *et al*. 2002; Seager *et al*. 2005). These observations detect the red edge feature at the 4% to 10% level and seem to confirm its potential use as a biosignature. The red edge feature has also been detected in low-resolution spectra of the Earth taken from the Galileo spacecraft (Sagan *et al*. 1993). Absorption features due to ozone, oxygen and water vapour, as well as the rise in the blue part of the spectrum due to Rayleigh scattering in the atmosphere are also seen.

Although in a single plant leaf the red edge is very prominent, in the integrated Earthshine spectrum it is only present at the few-percent level and may be very difficult to detect in the spectrum of an extrasolar planet, especially when unknown atmospheric features are present. The strength of the red edge is expected to be variable, however, since it will depend on the degree of cloud cover and the area of vegetation being illuminated, and this may help matters. Diurnal variations as an ELP rotates and vegetated areas come into view, may be easier to detect, as well as seasonal changes occurring during the planet's orbit (Seager *et al*. 2005). The use of the red edge as an extrasolar biosignature also assumes that similar photosynthetic structures and pigments to those on Earth will have evolved elsewhere. The increase in reflectance at 700 nm, giving rise to the red edge, is largely due to the cell structure in the leaves of terrestrial vegetation, which scatter light longward of this wavelength very efficiently. This may be an evolutionary mechanism to harvest light at shorter wavelengths whilst simultaneously keeping the leaf structure cool by not absorbing at longer wavelengths. If so,

then this could be an essential strategy for any land-based vegetation which might, therefore, readily evolve elsewhere (Seager *et al*. 2005).
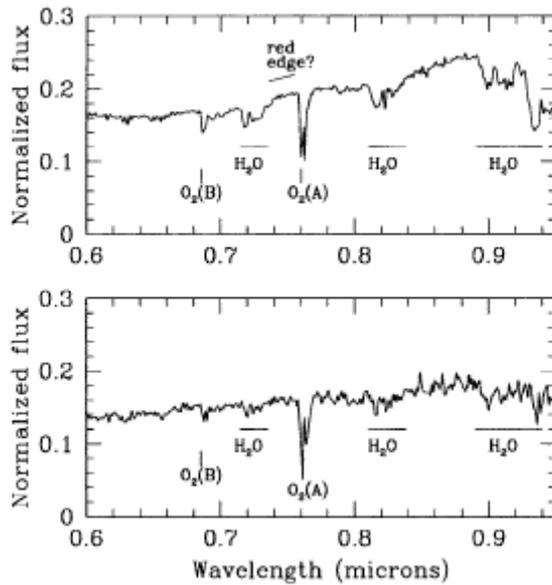

Figure 2. Earthshine observations (adapted from Seager *et al*. 2005) corresponding to vegetated (top) and non-vegetated regions of the Earth. A tentative detection of the red-edge feature is seen in the top spectrum when a vegetated area of the Earth (South America) is illuminated.

Approximately half of all photosynthesis on Earth is carried out by oceanic phytoplankton (Field *et al*. 1998), which does not, in general, exhibit a red-edge feature. Neither do all photosynthetic pigments have absorption bands in the same wavelength range as the chlorophyll A and B used by land plants. For example, purple bacteria use bacteriochlorophyll A and B, which have absorption peaks longward of 700 nm. A different light-harvesting system is used for phototrophic growth by halophilic Archaea, which are salt-loving extremophilic microorganisms, robust against UV radiation and tolerant of desiccation. They use a light-harvesting system featuring the retinal-based chemical bacteriorhodopsin, which has a broad absoption peak centred around the solar maximum of 550 nm. Interestingly, chlorophyll absorbs light either side of this peak, suggesting the possibility of evolutionary competition between the two, and that both systems may have been present in quantity throughout time (DasSarma 2004). The tolerance shown by halophilic Archaea for harsh cold, dry, and salty conditions makes this species a prime candidate for life on Mars, should it exist at the present

time (Landis 2001). Recently, retinal proteins similar to bacteriorhodopsin have been discovered in common planktonic bacteria in the oceans, which are spectrally tuned depending on their depth in the water column (Man *et al*. 2003). The rapid appearance of microbial life on Earth, and the lengthy period over which it dominated, renders it statistically likely that if extrasolar terrestrial counterparts are found, then they too may well be inhabited and even dominated by microbial life. However, the spectral detection of microbial life is likely to prove even more difficult than red-edge detection of vegetation (Knacke 2003), and will be a challenge for the post TPF/Darwin era.

5.   CHIRAL SIGNATURES

A characteristic of life is that it is predominantly homochiral. The vast majority of organisms use only left-handed L-amino acids in proteins and right-handed D-sugars in nucleic acids. This is likely to be a necessity for self-replication in which case it will characterize all biochemical life (Popa 2004). As mentioned in Section 2, analysis of the Murchison meteorite has shown L-excesses of up to 9% for a number of α-methyl amino acids (Cronin & Pizzarello 1997), with slightly smaller excesses found in the Murray meteorite (Pizzarello & Cronin 2000). This suggests that homochirality may result from the delivery to Earth of pre-biotic matter with an in-built enantiomeric excess (Bailey *et al*. 1998); alternatively, it may arise from a surface interaction that favours one handedness over the other. Nevertheless, chirality is a property of terrestrial life, and studies of chirality have been proposed as a robust means of searching for life that may even differ from terrestrial life.

Organic material displays optical activity, arising from differential absorption (circular dichroism) or scattering of left and right circularly polarized light by its component chiral molecules (Pospergelis 1969, Wolstencroft 1974, Wolstencroft *et al*. 2002b). Circular dichroism spectroscopy is a standard analysis technique for studying protein structure and function (Purdie & Brittain 1993, Kelly & Price 2000). Chlorophyll, for example, induces 0.1 - 1% circular dichroism in its absorption bands (Houssier & Sauer 1970), as shown in Fig. 3. The spectra of intact chloroplasts from plant leaves show additional peaks, probably due to the presence of other chromophores such as carotenoids (Faludi-Daniel *et al*. 1973). Circular Intensity Differential Scattering (CIDS) considers the circular polarization induced by scattering from chiral samples and has been studied by Bustamante *et al*. (1985). Circular polarization also can be caused by optical interaction associated with the chirality of subcellular structures,

such as membranes and macromolecules (Bustamante *et al*. 1983; Finzi *et al*. 1985). Light emitted through fluorescent processes, commonly associated with molecules of biological significance, also exhibits circular polarization (Steinberg 1978; Riehl & Richardson 1986). Microbes typically produce fractional polarizations ~10^{-2} to 10^{-3} (Salzman & Gregg 1984). It is clear that the interaction between light and living organisms can produce, in a wide variety of ways, a potentially detectable signal ~0.1% or more, in the form of circular polarization. While ocean water containing phytoplankton has been reported to produce fractional polarizations of the order of 10^{-4} at 488 nm (Voss *et al*. 1984), values near absorption bands may well be considerably higher.

Circular dichroism and related phenomena in photosynthesis can be induced by the intrinsic chirality of the molecules, by excitonic coupling between chromophores in molecular complexes and by macroscopic organization of the system (Garab 1996). The spectra of chlorophyll and bacteriorhodopsin show a substantial circular dichroism signal as well as a distinctive sign-flip through the absorption bands (Fig. 3).

Non-biological contributions to circular polarization can arise from atmospheric and aerosol scattering and from mineralogical scattering processes. While some minerals are also optically active, integrating over a naturally produced sample is expected to give equal fractions of enantiomorphs, which average to zero in their optical activity. Scattering can be a source of circular polarization if the scattering object itself has a chiral geometry.
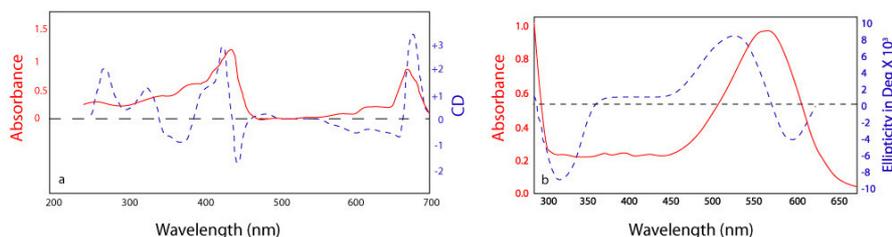

Figure 3. (a) Absorption spectrum of chlorophyll (red, solid) and circular dichroism spectrum (blue, dashed) adapted from Houssier & Sauer (1970). (b) Absorption spectrum (red, solid) and circular dichroism spectrum (blue, dashed) of bacteriorhodopsin, adapted from Becher & Cassim (1977).

Likewise, chiral asymmetry in the scattering system geometry, for example associated with preferential alignment of particles, can lead to artifacts, as can birefringence in the detection optics (Francke *et al*. 1994, Riehl & Richardson 1986, Rosen & Pendleton 1995). Multiple reflection and phase effects can also introduce circular polarization, but would produce a smooth

distribution recognizably related to the geometry of the scattering in the case of spatially resolved solar system observations (Bandermann *et al*. 1972, Degtjarev & Kolokolova 1992). Empirically, solar system measurements of circular polarization consistently find very low fractional circular polarization levels, ~10^{-4} to 10^{-5} (Kemp *et al*. 1971, Swedlund *et al*. 1973, Meierhenrich *et al*. 2002), some two or three orders of magnitude smaller than likely organic effects due to pure biological samples. Imaging circular polarimetry of the Martian surface at 210 km resolution (Sparks, Hough & Bergeron 2005) found upper limits to the polarization of ~10^{-3}, consistent with globally averaged values. Even if local enantiomeric excesses of optically active minerals were to exist, it is expected that they would be distinguishable from circular polarization having an organic origin by their spectral properties (Pospergelis 1969, Kelly & Price 2000).

The unique homochirality of biology can, therefore, potentially yield a macroscopic circular polarization signal especially in photosynthetic and phototrophic systems. From an astronomical perspective, these activities are extremely attractive, since they are surface phenomena and are likely to be tuned to the wavelength of maximum spectral flux of the host star (Wolstencroft & Raven 2002a). For the same reason they are also tuned to the wavelength of maximum transmission of the hypothetical planetary atmosphere. Both of these combine to maximize our ability to observe the source directly.

Circular-polarization spectroscopy has the potential to distinguish between an organic-based absorption feature and a mineralogical one, thus helping to eliminate features that can mimic the chlorophyll edge, yielding potential false positives. However, very few laboratory studies of the circular polarization signatures of intact biological materials (i.e. in macroscopic or whole cell form) have been undertaken to date (Wolstencroft *et al*. 2002b). Due to the potential for false positives, carefully designed studies are necessary to ensure that robust techniques are developed. In addition to biological targets, it is essential to investigate inorganic samples, such as pure minerals and mineral mixes (such as sand and rock), to establish whether circular polarization allows discrimination between strong edge features in organic and inorganic substances. Nevertheless, it is encouraging that no false positives were found by Sparks *et al*. (2005) in their imaging circular polarimetry of the Martian surface. Finally, it is essential to carry out terrestrial field studies to provide the necessary validation of these concepts in practical remote sensing applications.

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