Detectability of life and photosynthesis on exoplanets

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'Is there life on exoplanets?'. We refer to exoplanets as planets in other solar systems than our own. This often asked question can be further refined by asking 'is there life on exoplanets which is so extensive that it may impact on its atmosphere, its biosphere and its optical properties?'. And if such a life exists, at astronomical distances from us, can we detect it with instruments on Earth-based or Earth-orbiting observatories? Will then, in that case, our advanced knowledge of present-day and early-day photosynthesis on Earth help us select appropriate biosignatures that may signal its presence? Here we elaborate further on these themes, based on the most recent literature, and from the point of view of photosynthesis. We also provide our considered views. Although search for chlorophyll is considered desirable, we conclude that our best bet is to look for and analyse photosynthesis-related gases, namely O_2, CO_2 and H_2O vapour. We shall keep in mind that the evolutionary tree of life on our planet has its roots in autotrophy, and of the various forms of autotrophy, only oxygenic photosynthesis can produce massive amounts of reduced carbon and free O_2, both in water and on land.

It was not many years ago that the first planet was discovered in a foreign solar system. Further, progress in this field has been rapid and hundreds of 'exoplanets' (i.e. planets in solar systems other than ours) have now been discovered. Optical spectra have already been measured for a few of them: HD 109458b[1], HD 209458b[2] and HD 189733b[3]. For HD 189733b, chemical constituents have been determined[3]: in addition to putative $MgSiO_3$, there is a more certain identification of water[4] and methane[1], and for HD 209458b water has been also identified[2]. These particular planets are gas giants with much more mass than the Earth, somewhat analogous to Jupiter, but with higher surface temperatures due to their proximity to their parent stars. However, Raymond *et al*.[5] and Guedes *et al*.[6] have calculated that with high probability Earth-sized and Earth-like planets are present in habitable zones of systems with giant planets. It seems only a matter of time before rocky, Earth-sized planets can also be examined. Already exoplanets in the range of 5–10 Earth masses are beginning to be detected, and it is estimated that it is possible to detect habitable-zone exoplanets of only a few Earth masses at the distance (1.33 parsec = 4.25 light years) of Alpha Centauri[7]. Such planets are expected to be as rocky as the Earth. While larger planets have been discovered either by their periodic displacement of the mother star (and the resulting Doppler effect on starlight), or by the diminution of starlight as the planet passes between the star and the Earth, smaller planets around nearby stars have been detectable only by their effect on the orbits of the larger ones (though occasional evidence for small planets around distant stars can be found by gravitational microlensing). The first space telescope specifically designed to search for Earth-sized exoplanets is the recently launched Kepler[8] (http://www.kepler.arc.nasa.gov/). However, no results are yet available. Recently, techniques of adaptive optics and instrumental damping of the otherwise overwhelmingly bright starlight have permitted actual images of exoplanets to be obtained (see for example, Lafrenière *et al.*[9]). Figure 1 shows an artist's view of an exoplanet passing in front of its mother star.

The possible systems

Many authors have speculated on biospheres and organisms based on solvents other than water, and on chemistries for complex molecules other than the one based on carbon atoms, such as those with silicon skeletons. However, because fairly complex carbon compounds are present in the interstellar space, we believe that carbon-based life is what one should search for. Arguments made in favour of carbon-based life[10] include the following: (a) although silicon is also common, its flexibility to form complex molecules is much lower than that of carbon; (b) quite complex carbon compounds have been detected in the interstellar medium[11], and (c) the Earth, whose crust is composed of substantial amounts of silicates, does not harbour silicon-based life.

On the Earth most present-day life depends, directly or indirectly, on photosynthesis, but it was probably not the first life to appear. Chemosynthesis (lithotrophy) is still the way that many organisms power their activities, and lithotrophic organisms have been found deep down in the Earth's crust. We, however, focus on photosynthesis, because it dominates the present-day Earth and it is probably easier to detect than other metabolic systems. This is also what we suggest here.

The chlorophyll system

Earth organisms harvest energy from sunlight in two ways. Photosynthetic

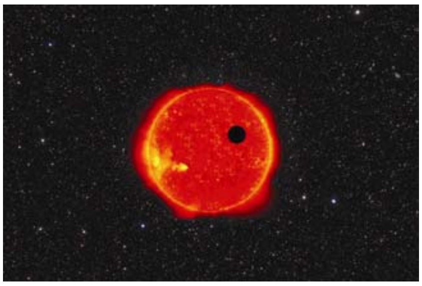

Figure 1. An artist's view of an exoplanet passing in front of its mother star. The planet is seen only as a black shadow, since the side towards the observer is not illuminated by light from the star. One way of detecting exoplanets is by the periodic decrease in starlight that they cause while transiting the star. Planets orbiting cool stars are favourite targets in the search for extraterrestrial life, because these stars are common, long-lived and burning in a stable manner.

bacteria, algae and plants use chlorophyll and chlorophyll-like pigments (mostly together with non-chlorophyll antenna pigments) to convert sunlight to redox potential which they use for moving electrons and carrying out redox reactions. An important consequence of this redox electron flow is the translocation of protons across the thylakoid membrane and the formation of transmembrane electrochemical potential (proton motive force (pmf)) which is used to generate ATP and other high-energy phosphates. Some archaea, on the other hand, use sunlight harvested by rhodopsin-type pigments to directly generate pmf which they use for the production of high-energy phosphates, as well as for pumping out Na^+ ions against the concentration gradient[12]. These two light-converting processes, i.e. light $\rightarrow$ redox potential $\rightleftarrows$ pmf and light $\rightarrow$ pmf are both quantitative and stoichiometric, meaning that light enters as a reagent in the relevant chemical reactions.

Other systems

The proteorhodopsin system: The dominance of chlorophyll-based photosynthesis may not be as total as hitherto thought. Thus we may have to look for other spectral signatures than those of chlorophyll-like pigments, when we search for photosynthesis pigments on exoplanets. Béjà *et al.*[13] and Gómez-Consarnau *et al.*[14] found that growth of various planktonic, marine, proteorhodopsin-containing bacteria is stimulated by light, and that they apparently use proteorhodopsin for harvesting sunlight. The phylogenetic diversity of such bacteria has, by now, been explored by several research groups.

The flavoprotein system: This system is different from photosynthetic light-harvesting systems: it is instead used for signalling. Here, the electron transport is mediated by flavoproteins, either via light absorption in the flavoproteins themselves[15], or using antenna pigments, as in some photolyases[16]. In a model experiment, a flavoprotein system has already been shown to mediate light-induced formation of ATP[17].

The ruthenium system: Several man-made systems for photochemical electron transport have been constructed. A highly promising one utilizes ruthenium compounds[18] such as the 'blue dimer'; it can be used to photooxidize water to molecular oxygen.

Biosignatures

The chlorophylls

Kiang *et al.*[19] and Stam[20] have discussed spectroscopic 'biosignatures' from photosynthetic pigments on exoplanets. Although the possibility of spectral detection of photosynthetic pigments on exoplanets by instruments in our solar system may be small, it is still worth pursuing. We do know that it is already barely possible to detect the signature of chlorophyll in light reflected from the Earth, and this is when we know what to look for; however, improvements in methods may change all this. A popular way of deriving the integrated reflection spectrum of the Earth is to measure the spectrum for the part of the Moon not illuminated directly by the sun (only indirectly by sunlight reflected from the Earth) and to divide that by the spectrum of the sun-lit part of the Moon[21–24] (Figure 2). Such a spectrum can be fitted well by a synthetic 'earthshine' spectrum in which reflectivity of vegetation is also a part[4,25,26], but to detect the signature of chlorophyll or vegetation in the measured spectrum may be difficult. Simulations by Arnold *et al.*[27] indicate that a 'supertelescope' with units spread out over 225 km would be required. It must be even harder when not knowing what to look for. However, we remain optimistic as new technology may someday surprise us. The prospect of a telescope with a size of 225 km is not as impossible as it may seem, as we can think of a telescope consisting of several units in space. For further information on earthshine measurements and related topics, see http://www.astro.lu.se/~torben/earthshine/ and http://www.bbso.njit.edu/Research/EarthShine/.

The gases (O_2, O_3 and CO_2)

Several constituents (H_2O, CO_2, O_2, O_3) of the Earth's atmosphere are easily seen in the Earth's reflection spectrum[21–23]. Despite its low concentration, perhaps, even the oxygen molecule dimer $[O_2]_2$ (or O_4) is discernable by its absorption[23] around 575 nm. Since ozone appears to be relatively easy to detect[28], the signature of oxygenic photosynthesis could be particularly amenable to detection by spectral measurements. However, molecular oxygen can also form abiotically[29]. It is present in tiny amounts on several of the moons in our solar system which nobody believes is inhabited by photosynthesizing organisms: Europa, Ganymede, Callisto, Rhea and Dione. This O_2, in small amounts, is mostly trapped in ice, and large atmospheric amounts are not expected to be produced abiotically. Thus, the biosignatures based on oxygen may indeed turn out to be important.

Kaltenegger *et al.*[30] have modelled the infrared emission spectra of the Earth throughout six geological epochs of its history, ranging from a CO_2-rich early atmosphere, via a CO_2/CH_4-rich atmosphere around 2 billion years ago, to a present-day atmosphere. The model includes H_2O, CO_2, CH_4, O_2, O_3, N_2O, and vegetation-like surface albedos.

Reid *et al.*[31] have attempted to estimate the age distribution of solar systems in our neighbourhood. They conclude 'If terrestrial planet formation is independent of the metallicity of the host star, then at least 25% of local systems are expected to be younger than 2.5 Gyr (2.5×10^9 years), a period during which Earth's atmosphere was anoxic. However, if the terrestrial planetary systems follow an age distribution similar to the known exoplanet host stars, then 40–50% of the Earth-analogs in the solar neighbourhood could be younger than 2.5 Gyr. Thus many of the planetary systems in our neighbourhood seem to be old enough that there would have been time for oxygen and ozone to have accumulated in the atmosphere, provided life had started and evolution had taken a course similar to that on the Earth.

Looking for life: M-star planets

It has been thought that the chance for life to develop would be greater on a planet orbiting a more long-lived star than the Sun, and planetary systems around low-mass M-type stars have been considered the prime candidates. M-stars are cooler than the Sun and one would expect photosynthetic pigments in such systems to have absorption peaks at longer wavelengths than for chlorophyll. This could present a problem for oxygen evolution. Already under terrestrial con-

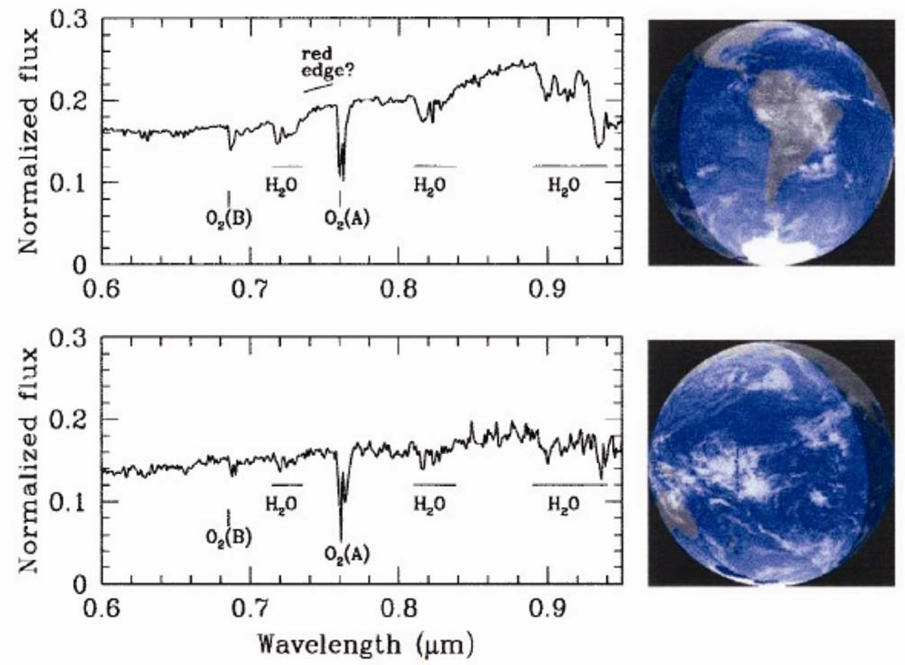

Figure 2. Reflectance spectra of the Earth obtained by dividing the spectrum of the Earth-illuminated part of the Moon by that of its Sun-illuminated part. (Right) Simulated images of the Earth as seen from the Moon show which part of the Earth the spectra refer to. Absorption bands of oxygen in the atmosphere are clearly visible and also water vapour bands can be discerned. The curve section marked 'red edge?' in the top spectrum is rising slightly with increasing wavelength. Possibly this is a 'signature' of land vegetation, since part of the spectrum should, in this case, be derived from vegetation in South America. The bottom spectrum, largely derived from the Pacific Ocean, lacks this special feature. The figure illustrates how difficult it is to see the spectral signature of vegetation even in an Earth spectrum, and how much easier it is to detect gases in the atmosphere. From Seager *et al.*[45].

ditions a sophisticated system is required for oxygenic photosynthesis. Water oxidation that leads to the production of oxygen and protons, takes place through the utilization of four positive charges that are produced as a consequence of primary photochemistry at reaction-centre chlorophylls[32]. It is necessary to have two photochemical systems connected in series, with both systems starting almost simultaneously, to achieve the necessary 'lifting' of electrons from water to a compound that can be used for reducing carbon dioxide; in addition, some energy is bound in high-energy phosphate that is also used in the assimilation of carbon dioxide. With a photosynthetic pigment absorbing at longer wavelength than chlorophyll and suited for harvesting the less energetic photons from an M-star, more than two photosystems would need to be connected in series to match the span in redox potential[19,33]. It would probably be a difficult task for evolution to achieve this even when given more time than the couple of billion years that it took on the Earth. One could imagine a quite different way of connecting photochemical systems in a series, not involving electron transport, but ion transport as the primary process. Electric fishes (as electric eels, electric rays and catfish) have structures reminiscent of voltaic piles, and with them they produce electric fields[34] of hundreds of volts per centimetre. It is done by pumping ions across membranes. We suggest that something resembling this should also be considered in a photosynthesis system.

Several characteristics may make M-star systems less suitable for life. M-stars are magnetically active and produce flares, which were thought to threaten any life in the potentially habitable zone, because this zone is so narrow and close to the M star. The closeness of any potentially habitable planet would also cause it to be tidally locked, with a big temperature difference between the illuminated and shaded sides. This was thought to threaten the stability of any atmosphere. Tarter *et al.*[35] have, however, suggested that this is not as dangerous as previously thought. Lammer[36] has discussed M-star habitability for life, and Scalo *et al.*[37] regard search for life on M-system planets to be a feasible endeavour. On the other hand, a tidally locked planet would not have as strong a magnetic field as the Earth, and protection from galactic cosmic rays would depend on the magnetic field of the star; and there would be no magnetic protection from charged particles emanating from the star.

Further, the magnetic activity of M-stars heats up their upper atmospheres, resulting in ultraviolet (UV) radiation. In case a planet has an oxygen-containing atmosphere, a protecting ozone layer would form, but this radiation might otherwise threaten life on its surface. On the other hand, UV radiation may aid the early stages in the origin of life, and when an M-star ages, the UV flux will weaken. Walkowicz *et al.*[38] have discussed UV radiation from M-stars and how it affects the likelihood of finding life in such systems. The question of the balance between the pros and cons of the UV flux cannot yet be settled.

Could we find out whether life exists on nearby habitable planets?

As already mentioned, Guedes *et al.*[6] found that it would be possible to detect nearly Earth-sized planets in a habitable zone at the distance of Alpha Centauri.

We recognize that:

- available measurements have been pushed to the limit; a very long observation time is needed;
- most other star systems are much more distant;
- the word ‘detect’ does not mean that the planet has been seen or imaged;
- certain atmospheric gases, such as methane or oxygen, are not in themselves certain signs of life; more must be known about the planet to put such a finding in context (spectra of atmospheric gases can be recorded either in absorption against the parent star, or as emission from the planet’s atmosphere); and
- detecting spectra of photosynthetic pigments at this distance is not feasible, as we can hardly spot terrestrial vegetation even in the earthshine spectrum.

The major problem in exoplanet imaging is that light from the planet is only an exceedingly small fraction of the light from the star around which it orbits. Separation of habitable planet light from starlight is particularly difficult in M-star systems, since the habitable zone is closer to the star than in our solar system. For obtaining maximum spatial resolution, we would in principle prefer to use short-wavelength light for imaging. On the other hand, it is at short wavelengths that the starlight is most intense in comparison with the thermal radiation from the planet, since the star is so much hotter (cf. Planck’s radiation law). Also, if instruments are positioned below the Earth’s atmosphere, distortion due to atmospheric turbulence increases rapidly with decreasing wavelength; the present-day adaptive optics to counteract this is not efficient for wavelengths below about 1 μm. One possibility of improving the contrast between starlight and light from the planet is to study polarized light[20]. Starlight is almost unpolarized (as is the heat radiation from the planet), while light reflected from the planet surface, especially if reflected from a liquid ocean (but also when reflected from vegetation and other surfaces or scattered in an atmosphere), is elliptically polarized. The angle of linear polarization varies with the position of the planet in its orbit. So any regularly rhythmic change in polarization can be ascribed to an orbiting planet (see Battersby[39] for a basic background).

Concluding remarks

We now summarize our conclusions as follows: (i) The most likely type of life that someday we may be able to detect seems to be based on carbon and its compounds with, mostly, first and second row elements (H, O, N). (ii) The evolutionary tree of this life has its roots in autotrophy, and although several autotrophy processes are known, only one of them does not depend on chemical energy supplies, i.e. photosynthesis (for origin of photosynthesis, see Nisbet *et al.*[40]). (iii) Among the two variants of photosynthesis, anoxygenic and oxygenic, only the latter can produce massive amounts of reduced carbon and free O_2, both in water and on land. (iv) From our experience on the Earth, the only sine qua non molecule of oxygenic photosynthesis is chlorophyll *a*[41]. We are, therefore, inclined to search for signals that relate either to chlorophyll *a* or to the reactants (CO_2) and products (O_2, H_2O) of oxygenic photosynthesis (for water vapour, see Tinetti *et al.*[42]). (v) The spectral signals of chlorophyll are too weak to be clearly detected (particularly for marine photosynthesis) at the present status of technology, even in earthshine spectra extracted from a comparison of the Sun-lit and Earth-lit parts of the Moon. (vi) More amenable to detection in the exoplanet atmospheres are photosynthesis-related gases, namely O_2, CO_2 and H_2O vapour. All three absorb in the infrared, a spectral region in which the disparity between star and planet luminosities is more favourable than in the visible range where chlorophyll signals are detected. (vii) Technology is moving fast and new, powerful and instrument-loaded telescopes are being developed for the ground, and for launch into space[43]. This will enable us to clearly look farther out in the universe (see for example, Falkowski and Godfrey[44]).

1. Swain, M. R. *et al.*, *Nature*, 2008, **452**, 329–331.
2. Barman, T., *Astrophys. J.*, 2007, **661**, L191–L194.
3. Lecavelier des Etangs, A., Pont, F., Vidal-Madjar, A. and Sing, D., *Astron. Astrophys.*, 2008, **481**, L83–L86.
4. Tinetti, G. *et al.*, *Nature*, 2007, **448**, 169–171.
5. Raymond, S. N., Mandell, A. M. and Sigurdsson, S., *Science*, 2006, **313**, 1413–1416.
6. Guedes, J. M., Rivera, E. J., Davis, E., Laughlin, G., Quintana, E. V. and Fischer, D. A., *Astrophys. J.*, 2008, **679**, 1582–1587.
7. Rivera, E. J. *et al.*, *Astrophys. J.*, 2005, **634**, 626–640.
8. Basri, G., Borucki, W. J. and Koch, D., *New Astron. Rev.*, 2005, **49**, 478–485.
9. Lafrenière, D., Jayawardhana, R. and van Kerkwijk, M. H., *Astrophys. J.*, 2008, **689**, L153–L156.
10. Rothschild, L. J., *Philos. Trans. R. Soc. London, Ser. B*, 2008, **363**, 2787–2801.
11. Beltrán, M. T., Codella, C., Viti, S., Neri, R. and Cesaroni, R., *Astrophys. J.*, 2009, **690**, L93–L97.
12. Danon, A. and Stoeckenius, W., *Proc. Natl. Acad. Sci. USA*, 1974, **71**, 1234–1238.
13. Béja, O. *et al.*, *Science*, 2000, **289**, 1902–1906.
14. Gómez-Consarnau, L. *et al.*, *Nature*, 2007, **445**, 210–213.
15. Asard, H., Horemans, N., Briggs, W. R. and Caubergs, R. J., *Photochem. Photobiol.*, 1995, **61**, 518–522.
16. Henry, A. A., Jimenez, R., Hanway, D. and Romesberg, F. E., *ChemBiochem.*, 2004, **5**, 1088–1094.
17. Kolesnikov, M. P., Telegina, T. A., Lyudnikova, T. A. and Kritsky, M. S., *Origins Life Evol. Biosphere*, 2008, **38**, 243–255.
18. Liu, F., Concepcion, J. J., Jurss, J. W., Cardolaccia, T., Templeton, J. L. and Meyer, T. J., *Inorg. Chem.*, 2008, **47**, 1727–1752.
19. Kiang, N. Y. *et al.*, *Astrobiology*, 2007, **7**, 252–274.
20. Stam, D. M., *Astron. Astrophys.*, 2008, **482**, 989–1007.
21. Woolf, N. J., Smith, P. S., Traub, W. A. and Jucks, K. W., *Astrophys. J.*, 2002, **574**, 430–433.
22. Hamdani, S. *et al.*, *Astron. Astrophys.*, 2006, **460**, 617–624.
23. Turnbull, M. C. *et al.*, *Astrophys. J.*, 2006, **644**, 551–559.
24. Arnold, L., Gillet, S., Lardière, O., Riaud, P. and Schneider, J., *Astron. Astrophys.*, 2002, **392**, 231–237.
25. Tinetti, G. *et al.*, *Astrobiology*, 2006, **6**, 881–900.
26. Arnold, L., *Space Sci. Rev.*, 2008, **135**, 323–333.
27. Arnold, L., Bréon, F.-M. and Brewer, S., *Int. J. Astrobiol.*, 2009; http://arxiv.org/abs/0901.1214).
28. Ehrenreich, D., Tinetti, G., Lecavelier des Etangs, A., Vidal-Madjar, A. and Selsis, F., *Astron. Astrophys.*, 2006, **448**, 379–393.

29. Segura, A., Meadows, V. S., Kasting, J. F., Crisp, D. and Cohen, M., *Astron. Astrophys.*, 2007, **472**, 665–679.
30. Kaltenegger, L., Traub, W. A. and Jucks, K. W., *Astrophys. J.*, 2007, **658**, 598–616.
31. Reid, I. N., Turner, E. L., Turnbull, M. C., Mountain, M. and Valenti, J. A., *Astrophys. J.*, 2007, **665**, 767–784.
32. Wydrzynski, T. J. and Satoh, K. (eds), Photosystem II. The light-driven water plastoquinone oxidoreductase. In *Advances in Photosynthesis and Respiration*, Series Editor, Govindjee, Volume 22, Springer, Dordrecht, The Netherlands, 2005, p. 786.
33. Raven, J., *Nature*, 2007, **448**, 418.
34. Caputi, A., Carlson, B. and Macadar, O., In *Springer Handbook of Auditory Research, vol. 21 (Electroreception)*, Springer, New York, 2005, pp. 410–451.
35. Tarter, J. C. *et al.*, *Astrobiology*, 2007, **7**, 30–65.
36. Lammer, H., *Astrobiology*, 2007, **7**, 27–29.
37. Scalo, S. *et al.*, *Astrobiology*, 2007, **7**, 85–166.
38. Walkowicz, L. M., Johns-Krull, C. M. and Hawley, S. L., *Astrophys. J.*, 2008, **677**, 593–606.
39. Battersby, S., *New Sci.*, 2004, **182**, 36–40.
40. Nisbet, E. G., Cann, J. R. and van Dover, C. L., *Nature*, 1995, **373**, 479–480.
41. Björn, L. O., Papageorgiou, G. C., Blankenship, R. E. and Govindjee, *Photosynth. Res*., 2009, **99**, 85–98.
42. Tinetti, G. *et al.*, *Nature*, 2007, **448**, 169–171.
43. Labeyrie, A. *et al*., *Exp. Astron*., 2009, **23**, 463–490.
44. Falkowski, P. G. and Godfrey, L. V., *Philos. Trans. R. Soc. London, Ser. B*, 2008, **363**, 2705–2716.
45. Seager, S., Turner, E. L., Schafer, J. and Ford, E. B., *Astrobiology*, 2005, **5**, 372–390.

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