Detection and spectroscopy of exo-planets like Earth

J.R.P. Angel, J.H. Burge and N.J. Woolf
Center for Astronomical Adaptive Optics, Steward Observatory,
University of Arizona, Tucson, Arizona, 85721

ABSTRACT

Planets with mass similar to Jupiter's are now known to orbit nearby stars[1,2,3]. Are there also planets like Earth? If so, their thermal emission should be directly detectable, and thermal spectra could identify the strong features of carbon dioxide, water and ozone at the levels seen in Earth. But the very close angular separation (~0.1 arcsec) and huge brightness difference (~10^7) between a star and such a planet present a technical challenge. Space interferometry could in principle solve both problems, by using destructive interference to cancel out the stellar emission, and aperture synthesis to recover high angular resolution images. We show how these two functions conflict, and point to a new interferometer design which allows them to be reconciled. One key technical challenge is to combine beams with strictly controlled amplitude and achromatic phase inversions, so as to cancel the stellar disc flux by a factor of a million. We show how refractive elements analogous to an achromatic lens can be used for this purpose.

Key words: stellar interferometry, extra-solar planets

1. INTRODUCTION

The interferometer concept presented at the conference is the subject of a paper by the authors to be published in the Astrophysical Journal. We refer the reader to this paper for a full description, and to Scientific American[4] for a popular discussion. Here we give the basic principles behind interferometry to detect planets of other stars, and describe a beam combination method currently under investigation.

Suppose a star is like the sun, and we want to detect and study a planet like the Earth that might be present, one with the same orbital radius, mass, temperature, and atmosphere modified by the presence of life. To sample a few dozen suitable stars we need to look out to about 10 pc distance. At this distance, a planet with an orbital radius of 1 AU will appear up to 0.1 arcsec from the star. With the same size and albedo as the Earth, its reflected light it will appear 10^{10} times fainter than the star, but the reradiated thermal flux ratio is only 10^7, at the emission peak at 10 μm. The contrast ratio is thus 1000 times more favorable in the infrared. The infrared spectrum will give the planet's temperature, and could show the presence of the greenhouse gases, carbon dioxide, water and ozone, that show up as prominent absorption features in the 7 - 17 micron wavelength spectrum of the Earth (Angel, Cheng and Woolf, 1986)[5].

With the naked eye one can distinguish Venus in the daytime sky, provided it is not to close to the sun. Could similar direct resolution of the thermal emission of a stellar planet be obtained with a telescope with some kind of apodization or coronograph? Angel, Cheng and Woolf proposed an apodization method to reduce the halo of diffracted light which is especially problematic at longer wavelengths. It would reduce the first dark ring in the diffraction pattern of a filled aperture telescope to 10^{-5} of its peak value, at an angular radius of $2\lambda/d$, low enough to allow detection at the 10^{-7} contrast ratio in the infrared. It seems physically implausible that such strong reduction could be realized at significantly smaller radii. Thus for a planet at 0.1 arcsec separation, and the desired upper wavelength of 17 microns, a telescope diameter ≥70 m would be required. It would have to be operated in space at cryogenic temperatures to remove its own thermal emission, and the reflecting surfaces would have to be about as smooth as the Hubble mirror to avoid an unacceptably bright halo of scattered light around the star. Constructing such a large telescope in space is not completely excluded, but clearly goes beyond current technology and a realistic budget.

2. INTERFEROMETRY FOR VERY HIGH CONTRAST

We turn then to interferometric methods, allowing much smaller apertures to be used, and permitting the use of destructive interference to suppress the stellar emission. Consider first the simplest case of a two element interferometer; the angular fringe spacing is given by λ/s, where s is the baseline. By choosing the right baseline and phase relationship, we can arrange for destructive interference at the star, while the first constructive interference peak is at the planet 0.1 arcsec away. To reach λ = 17 μm, we would need s = 17 m. We have the choice of combining the beams so that fringes are formed in the focal plane, or on the sky. In the first case, the optical system obeys the sine condition, and each object in the field results in an image in the focal plane which has a full width given by the individual apertures, and is crossed by fringes corresponding to angular separation λ/s on the sky. A planet separated by half a fringe width could in principle be detected by an imaging detector as a brightening

 0277-786X/97/$10.00

in the dark fringes crossing the stellar image. But the sensitivity would be poor, because only that small fraction of the planet flux that underlies the darkest parts of the stellar fringe pattern could be detected. The rest is swamped by photon noise inherent in the very strong stellar photon flux.

It is much better to use beam combination that places the fringes on the sky, as in a radio interferometer. This can be done by directly interfering the infrared radiation, using a semitransparent beamsplitter to bring the stellar wavefronts from the two telescopes into coincidence. If images are then formed from the two beamsplitter outputs, they will show no spatial structure, but will vary in intensity according to the phase difference. If the optics are arranged so that at one output the wavefronts from the star have equal amplitude but opposite phase, independent of wavelength, then the stellar energy in that output is nulled, being all transferred to the other output. In this case all the radiation from a neighboring planet at angular separation $\lambda/2s$ will appear in full strength while the star is nulled at the same output. This is the principle of the nulling interferometer proposed by Bracewell for planet detection nearly 20 years ago[6].

The individual telescope elements can in principal be quite small - 1 m elements would have a beam width of 2 arcsec at 10 microns, large enough to include planets out to 10 AU for a system at 10 pc. The fluxes would be small, but detectable given that spatial resolution is not necessary. Spectral resolution of about 20 is required, not only to record the absorption features, but also to reconstruct images, because of the wavelength dependence of interference fringe spacing. The flux from an Earthlike planet at 10 pc is about 12 photons per minute per m^2 in 0.5 μm bandwidth.

3. COMBINING NULLING WITH AN IMAGING CAPABILITY

If the target were simply an unresolved star with a single planet, then a Bracewell interferometer would allow isolation and analysis of the planet's radiation. In practice, we must allow for the finite angular size of the star, multiple planets, and for the presence of a relatively bright cloud of diffuse thermal emission about the star, like the sun's zodiacal cloud. Jupiter, Venus and Mars have thermal emission comparable to the Earth's, and the zodiacal cloud is several hundred times brighter.

Can an interferometer configured for destructive interference of starlight also be used to reconstruct an image of the planetary system, to allow distinction of these components? Let us recall the requirements for aperture synthesis, the well established technique for imaging in radio astronomy. It does allow detailed image to be reconstructed from a simple two element interferometer. For the image of the north galactic pole made by Ryle and Neville[7], the u-v plane was filled by varying the separation of two elements, and by taking advantage of Earth's rotation. How far can these steps be duplicated by a nulling space interferometer? Rotation of a space interferometer about the line of sight to the star would be straightforward, provided the elements are connected by a beam. Varying the beam length could be difficult and risky, but we find that for continuum sources, observations at different wavelengths make an effective substitute. What is not possible is to combine the beams to give two signals in phase quadrature, to obtain complex phase. A useful planet signal can be obtained only when the stellar fluxes are combined in antiphase. The result of this restriction is that exactly the same signals are recorded after a 180 degree rotation of the interferometer, and so in the reconstructed image every object appears twice, mirrored on either side of the star. This becomes a serious flaw if the resolution is poor, because then a planet cannot be distinguished from a dust cloud seen edge-on. Galileo mistook Saturn's rings for two symmetric moons. Given the doubling of planets in a reconstructed image, we need good resolution to distinguish a weak planet in the presence of a strong dust cloud.

Normally we are at liberty to increase the baseline of an interferometer to improve resolution, but this can lead to a serious conflict with the requirement for nulling. When the baseline of the two element interferometer is extended, the central dark fringe is narrowed. The star has a finite size disc, and a perfect null is achieved only along a narrow band at the center of the achromatic dark fringe. How much energy leaks through? Consider the situation in which the fringe spacing is such that the planet at 1 AU lies at 1.5 fringe spacings from the star, about the minimum to obtain significant resolution. The transmission varies as $\sin^2\theta$, with θ is 3π at 1 AU. It follows that at the edge of the disc, at radius 0.005 AU for the sun, that $\theta \sim .05$ radians, and $\sin^2\theta \sim 0.0025$. The star leak is unacceptable, being about 10,000 times brighter than the planet. Star photon noise would prevent planet detection.

To overcome this problem, we have devised a 4-element, co-linear nulling configuration, which gives exceptionally deep and broad destructive interference near the symmetry axis. This is achieved by configuring the elements as two nulling pairs of different baseline, about the same center. The outputs from each pair are combined so as to contribute equal amplitude but opposite phase. In this way not only is the combined amplitude zero for a star on the symmetry axis, so is its first and second derivative with respect to angle off-axis. Transmission near the null in this case varies as the sixth power of the off-axis angle, instead of the quadratic dependence for the 2-element interferometer. With this configuration, very narrow fringes corresponding the baselines of 50 m or more are possible while maintaining star disc suppression of the whole stellar disc to a part in 10^7. The narrow fringes from the 4-element pattern are not sinusoidal, and result in complex signal modulation patterns as the interferometer is rotated. We find that true images can be reconstructed from the output signals by a cross correlation method analogous to aperture synthesis. A beam width of 20 milliarcsec (FWHM) or better can be reconstructed, allowing clear distinction of unresolved planet and smooth zodiacal cloud.

Provided the interferometer is located several AU from the sun to avoid local zodiacal emission, the noise should be dominated by photon noise from the uncancellable flux of zodiacal emission from the remote system (Leger et al., 1996)[8]. Assuming this emission is similar to that in the solar system, then integration of about a day are required to show Earth-like planets in a system at 10 pc, and several months integration will be needed to obtain spectra with the signal/noise ratio needed to detect ozone at the level seen in the Earth's spectrum.

4. BEAM COMBINATION FOR ACHROMATIC DESTRUCTIVE INTERFERENCE

Good star cancellation requires the wavefronts from different element pairs to be combined with precisely π phase difference, independent of wavelength. The intensity of the two beams must be matched to 0.1% and the pi phase shift must be maintained to 0.001 radians to adequately cancel the star.

We are exploring the potential for achromatic wavefront phase delay to be accomplished with balanced refractive materials, analogous to achromatic lenses. Preliminary indications are that bandwidths of $\Delta\lambda/\lambda = 0.2$ can be realized in the 5 - 18 μm range, using combinations of materials with different dispersions. The whole range can be thus covered in about 5 bands. Figure 1 shows the phase error for such a five band system that uses ZnSe and CsI as the dispersive materials. The thickness of the materials is optimized so that the π phase shift is maintained to 0.3×10^{-3} radians over the corrected bandwidth. Figure 2 shows the quality of the null that can be achieved using this design. These plots show that the CsI and ZnSe combination is outstanding from 9- 11 um. We anticipate that similar performance could be obtained by picking more optimal pairs of materials for each band, rather than using the same two materials for all bands.

This five band system will require the interferometer to have five independent channels. We envisage the use of a prism spectrograph at each of the 4 interferometer telescopes to split the light into the appropriate bands. Five discrete retro reflectors along the focused spectrum would pick off light for the independent channels and return the light back through the spectrograph to be recombined. By making differing out of plane displacements at the retro reflectors, the result will be five separated, diffraction-limited, quasi-achromatic star images, covering between them the full spectral range. From there on, the interferometer combining optics would be separate for each channel. This would allow very high coupling and transmission efficiency, with tailored optical coatings. Prior to detection, each channel would be further separated by wavelength, to yield about 20 wavelength bands in total.

5. ACKNOWLEDGMENTS

This work has been supported by the Air Force Office of Scientific Research (F49620-1-0437), NSF (AST92-03336), and NASA (NAS7-1260).

REFERENCES

1. M. Mayor and D. Queroz, *Nature*, **358**, 355 (1995).
2. G. W. Marcy and R. P. Butler, preprint (1996).
3. D. W. Latham, T. Mazeh, R. P. Stefanik, M.Mayor, and G. Burki, *Nature*, **339**, 38 (1989).
4. J. Roger P. Angel and Neville J. Woolf, *Scientific American*, **274**,(4), 60-66 (1996).
5. J. R. P. Angel, A. Y. S. Cheng, and N. J. Woolf, *Nature*, **322**, 341 (1986).
6. R. N. Bracewell, *Nature*, **274**,780 (1978); R. N. Bracewel and R. H. Macphie, *Icarus*, **38**, 136 (1979); R. H. Macphie, and R. N. Bracewell, in Instrumentation in Astronomy I II, ed. D. L. Crawford, *Proc SPIE*, **172**, 271-278 (1979).
7. M. Ryle, and A. C. Neville, *MNRAS*, **125**, 39 (1962).
8. A. Leger, J-M. Mariotti, B. Mennesson, M. Ollivier, J. L. Puget, D. Rouan, and J. Schneider, preprint (1995).

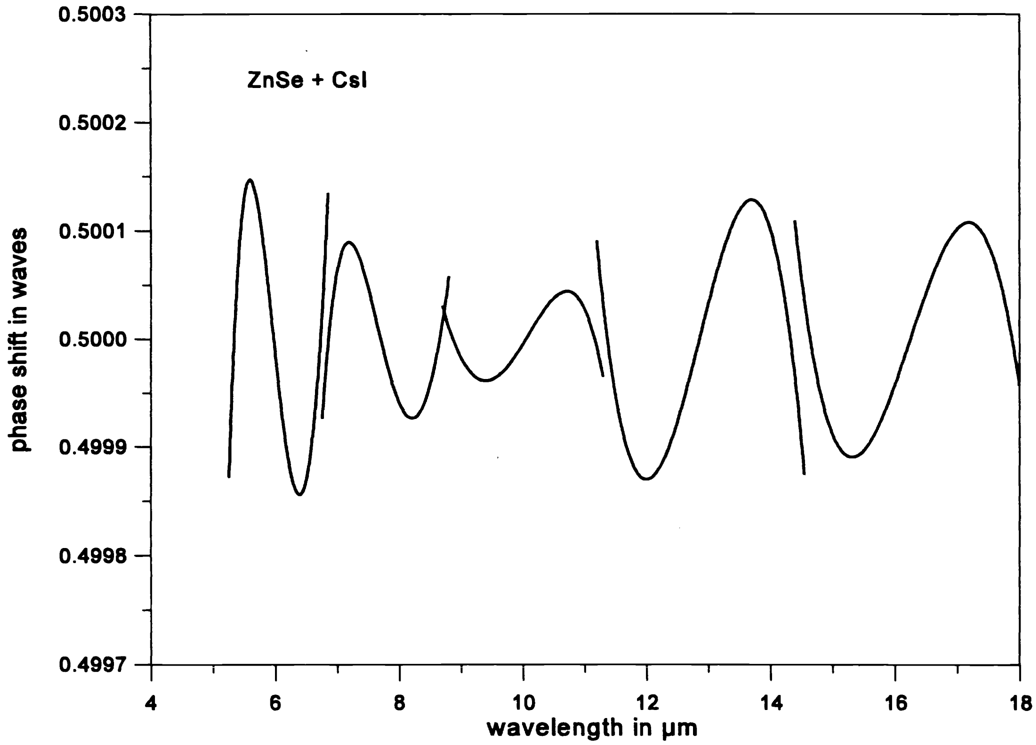

Figure 1. Relative phase shift between the two beams with optimized ZnSe and CsI dispersive compensators. The spectrum was divided into 5 bands which were individually achromatized.

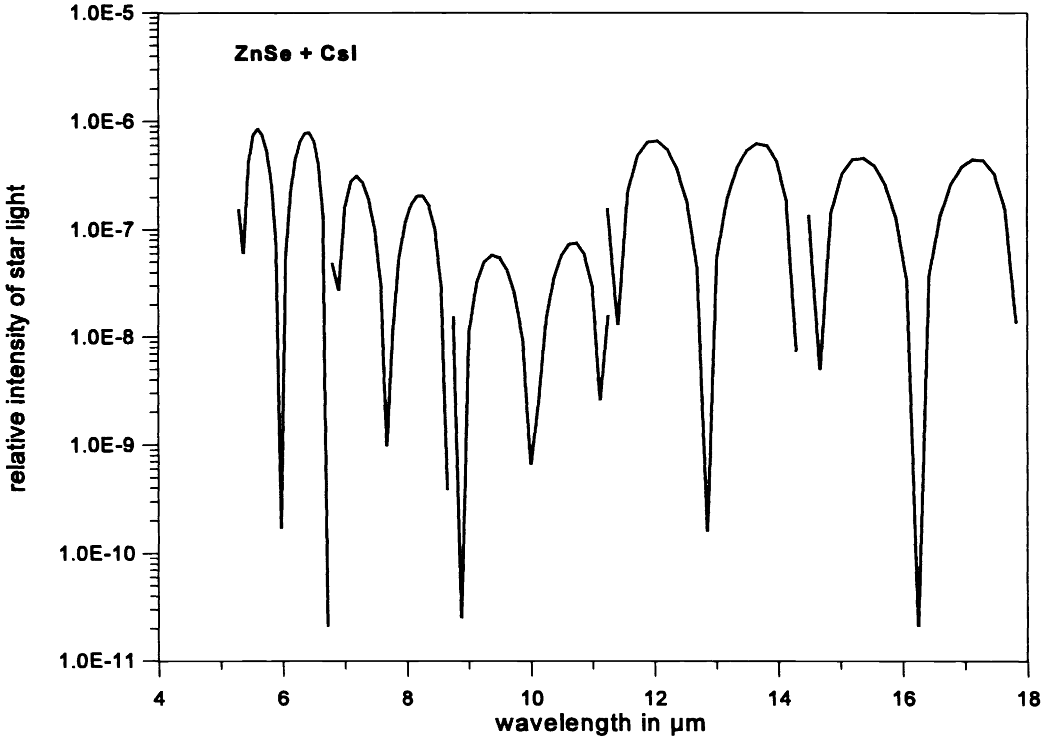

Figure 2. Rejection of star light for achromatic phase compensation shown in Figure 1.