Bioastronomy 2002: Life Among the Stars
IAU Symposium, Vol. 213, 2004
R.P.Norris and F.H.Stootman (eds.)

Finding Planets – How do you do it?

C. G. Tinney

Anglo-Australian Observatory, PO Box 296, Epping 1710, Australia

Abstract. Current and future planet search strategies are reviewed.

1. Introduction

In the years since the discovery of the first gas-giant extra-solar planets in 1995 (Mayor & Queloz 1995; Marcy & Butler 1996; Butler & Marcy 1996), interest in the search for planets outside our solar system has exploded (see Fig. 1a). Entire conferences are now devoted entirely to the subject of searching for planets – some recent meetings (the proceedings for most of which are still in press) include: First Eddington Workshop on Stellar Structure and Habitable Planet Finding, 11 - 15 June 2001 (Battrick 2002); Planetary Systems in the Universe, IAU Symposium 202 (in press); Planetary Systems and Planets in Systems, Saas Fee, 2-6 September 2002 (in press); Scientific Frontiers in Research on Extrasolar Planets, Carnegie Institution Washington, June 18-21, 2002 (in press); Techniques for the detection of planets and life beyond the solar system, Royal Observatory, Edinburgh, 7-8 November 2001 (Penny & Collier-Cameron, 2002). There are also review papers on various aspects of this search in this proceedings by G. Marcy, C. Beichman, D. Koch, P. Sackett, R. Jayawhardana, V. Meadows and others. This small review can't possibly hope the cover this subject in detail – it is more a "meta-review". For a more extensive review (as at March 2000) consult Perryman (2000).

2. Planet Detection

Table 1 attempts to summarise the techniques (both currently available, and those foreseen) into *very* broad categories, and to highlight some of their major advantages and disadvantages.

The basic problem in detecting planets is very simple. Stars are bright, and very massive. Planets are dim, and not very massive (at least in comparison to stars), and are seen very close to their parent stars on the sky. So detecting light coming directly from a planet is hard, because the "glare" light from the star swamps the planetary light. And detecting the indirect effects of the planet on the star itself (like changes in the motion of the star across the sky, or the Doppler velocity variations of the star, due to the planet's gravitational pull) is also hard because these effects are small.

2.1. Direct Detection - The Scale of the Problem

Consider a hypothetical external observer trying to observe our Solar System in a direct search for planets. Jupiter is far-and-away the easiest to find, but

https://doi.org/10.1017/S0074180900192915 Published online by Cambridge University Press

even so is a factor of $\sim 10^{10}$ times fainter than the Sun the visible (λ=0.4-0.6 nm). In the infrared (λ=2-10 μm) the brightness ratio is more favourable – a mere factor of $\sim 10^7$. Most planet searches tend to target stars within about 50 pc[1]. At this distance an external observer would see Jupiter seperated on the sky from the Sun by 0.1 arcsec. The best image quality currently achieved by astronomomical instruments is currently around 0.1 arcsec (full-width at half maximum). So our hypothetical observer is trying to detect a small blip of light due to Jupiter against a glaring background that is $\sim 0.5\times10^9$ times brighter (in the visible) or $\sim 0.5\times10^7$ (in the infrared). Robust detection in such conditions is impossible – major technological advances in astronomical image quality, or in image cancellation are required. It is also clear that the detection of much smaller (and so much dimmer) terrestrial planets is even harder by yet more orders-of-magnitude.

Despite this, direct detection remains a "Holy Grail", because one can tell so much about a directly detected planet. Its albedo can be measured, its orbit can be mapped directly, and spectra of its surface can be acquired. So it is being pursued, and headway can be made in a few special cases. In particular, when planets are young, their gravitational contraction produce more luminosity than the starlight they reflect. The search for young planetary systems via direct dection in the infrared, therefore, has been a significant area of recent activity (e.g., Luhman & Jayawardhana 2002; Liu et al. 2002; Jayawardhana 2004).

Another special case is the detection of planets via their GHz synchrotron and/or MHz cyclotron radio emission. At these wavelengths the contrast between star and planet is much smaller than that due to thermal and reflected radiation in the optical and near-infrared (e.g., Bastian, Dulk, & Leblanc 2000; Zarka et al. 2001; Farrell et al. 2004)

2.2. Indirect Detection - The Scale of the Problem

Now consider the indirect detection problem – our hypothetical observer wants to detect the gravitational effect of Jupiter on the Sun. She can either look for physical motions of the Sun across the sky ("astrometric wobble"), or induced motion along the line of sight as revealed by velocity variations ("Doppler wobble"). In either case the effects are small. The astrometric wobble is at the level of $\sim$0.2 milli-arcseconds (mas) (Fig. 1b), which requires positional measurement at the level of $1/500^{th}$ of the very best current astronomical image sizes. The Doppler wobble is at the level of 10 ms^{-1} (see Fig. 6 in Butler et al. 2002) – again a tiny fraction of the velocity resolution of most astronomical instruments. Moreover, these indirect observations must be carried out at these ridiculous precisions over long periods of time – 11.86 years for the detection of a Jupiter-analog.

In both the astrometric and radial velocity cases, these are extremely difficult measurements to perform. No confirmed astrometric detections of extra-solar planets have yet been made from the ground, though development in ground-based interferometry continues apace at Keck (Colavita & Wizinowich

[1] At a distance of 1 parsec (pc), a linear distance of 1 astronomical unit (a.u., or one Earth-Sun distance) subtends an angle on the sky of 1 arcsec ($1/3600^{th}$ of a degree). 1 pc = 3.0856×10^{16} m = 3.26 light year. 1 AU = 1.49598×10^{11} m.

https://doi.org/10.1017/S0074180900192915 Published online by Cambridge University Press

Table 1. A Summary of Planet Detection Techniques

Technique	Success[a]	Pluses	Minuses
Current Searches			
Direct	N	Wonderful, but	Primary brightness. Large contrast Special cases only.
Transit	C	Determine planet radius.	Mega-star samples needed.
		Low-mass sensitivity.	V>14 stars inaccessible to other techniques
Gravitational	?	Statistically powerful	Unrepeatable. Distant Planets.
Astrometry	N	Measures everything	Sensitivity $\propto$ 1/Distance
Radial Velocity[b]	Y	Hugely successful to date.	Unknown orbit inclination
		Can find Jupiter-analogs.	Can't find terrestrials.
The Future in Space			
Astrometry	-	Measures everything	Space
Transit	-	Determines radius. Brighter targets accessible to follow-up	Space
Direct	-	Light from planets. Terrestrial planets	Space

a - Y: Has discovered new planets. N: No success yet. ?: Unclear.
C: Has confirmed planets from other techniques, but not discovered new planets.
b - Pulsar timing is included in the "Radial Velocity" category.

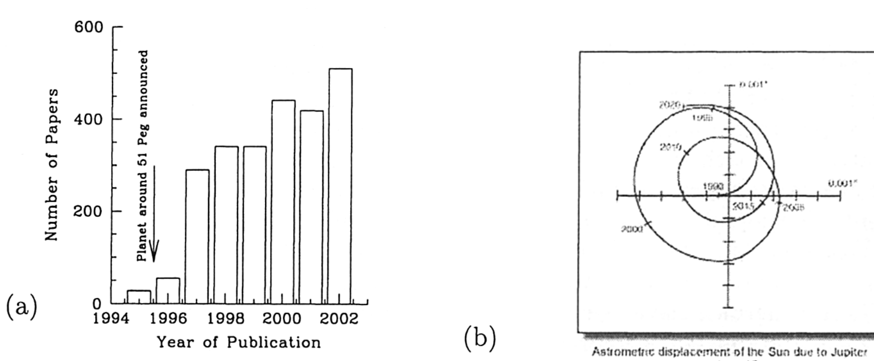


Figure 1. *(a)* Histogram of number of papers per year with the word "planet" in their text from five leading US journals. *(b)* Astrometric wobble of the Sun due to Jupiter as seen from 10 pc. An observer at 50 pc sees the same pattern, but 5× smaller. Credit: `planetquest.jpl.nasa.gov`.

https://doi.org/10.1017/S0074180900192915 Published online by Cambridge University Press

2000), ESO's VLT (Glindemann 2001), Palomar (Colavita et al. 1999) and USNO (Pauls 2001; Armstrong et al. 1998). All astrometric measurements involve determining the position of a target star relative to some reference frame (usually another star, or set of stars). The Earth's atmosphere, however, moves both target and reference star semi-independently. Ground-based interferometers must track these motions in attempt to cancel them, but there is a limit to the efficiency of this process. More significant headway can be made in space, which I discuss below.

2.3. Radial Velocity

Radial velocity (or "Doppler wobble") techniques have had all the successes in to date extra-solar planet detection. Starting with the (usually neglected) pulsar planets in 1992 (Wolszcan & Frail 1992; Wolszcan 1994), and followed by the first detections of gas giant planets around main-sequence stars in 1995 (Mayor & Queloz 1995; Marcy & Butler 1996; Butler & Marcy 1996). The number of planets claimed to have been detected, and widely accepted, is now in the region of one hundred. Even so, the observations required to detect these planets are difficult. As discussed above, detecting a Jupiter-like planet in a Jupiter-like orbit requires the detection of a $10\,\mathrm{ms}^{-1}$ radial velocity amplitude with an 11.86 year period. This drives searches to velocity precisions of $3\,\mathrm{ms}^{-1}$ or less for each observation. This represents a tiny fraction (typically $\sim 1/1000^{th}$) of the intrinsic velocity resolution of the astronomical spectrographs in use. It is therefore not enough to simply collect lots of photons from each star in order to obtain a more precise velocity estimate – fantastic control of the shape and nature of the spectrograph's intrinsic velocity response (its "point-spread function") must be maintained. *Moreover* such control must be systematically retained over timescales of more than 10 years!

To date, two philosphies have been followed to maintain this level of control. The first is simply to build a very stable spectrograph. This is the approach followed my most teams, including the programs at La Silla and the Observatoire de Haute-Provence (Queloz et al. 1998), McDonald Observatory (Cochran 1997), AFOE (Noyes et al. 1997). Even more precise control is being targetted by the HARPS spectrograph under contruction for use on the ESO 3.6 m telescope. An alternative approach is to hyper-calibrate the instrument with a known spectral profile which is imprinted on every spectrum acquired. This is the approach originally developed by Butler & Marcy (1996) and now used by the teams at Lick (Fischer et al. 2001), Keck (Vogt et al. 2000), AAO (Tinney et al. 2001; Butler et al. 2001) and also implemented by Kürster et al. (2000).

These programs have been remarkably successful – almost everything we have learned about extra-solar planets in the last 7 years has come from their detection and characterisation by radial velocity searches (Marcy 2002; Butler et al. 2002; Perryman 2000; Marcy & Butler 1998a, b; Nelson 2001), and we can expect these programs to continue to provide more insights as their time baselines extend, which in turn will extend their sensitivities to more and more Solar System-like systems. Their major weakness is that, although they provide dynamical information on the detected planets (i.e., information on mass, as well as orbital periods, eccentricities and sizes) they do so only to within an unknown $\sin i$ term (where i is the inclination of the planet's orbit to the line of sight). Statistically, i will be uniformly distributed, but large samples of planets are needed to robustly infer underlying trends.

2.4. Photometric Transit Detection from the Ground

A potentially powerful way to find, and characterise, planets is to search for transits of their parent star. Such transits can not only reveal the presence of a planet, but also provide information on the planet's physical size and potentially on its atmosphere.

Unfortunately the probability[2] of an individual planetary system transiting are small : $\sim$0.3% for a Jupiter-analog, or $\sim$0.5% for an Earth-analog. For 51 Peg-like planets (i.e. gas giant planets orbiting within 0.1 AU) probabilities are much larger $\sim$10%. And indeed the only extra-solar planet yet detected to transit is just such a planet, orbiting the star HD 209458 (originally discovered from radial velocities, and subsequently found to transit - Henry et al. 2000).

The real power of transit detection is that it can potentially detect even very low-mass, terrestrial planets – however, once again, the requirements are challenging. The dimming produced by a planetary transit ($\propto r^2_{planet}/R^2_{star}$) is $\sim$1% for a 51 Peg-like planet or a Jupiter analog, but just 0.01% for an Earth-like planet. The atmosphere means that continuous photometric measurements at the 0.01% level are difficult, or impossible, for ground-based telescope. Nonetheless, extensive searches for Jovian mass planets are taking place (e.g., STARE: Brown & Charbonneau 2000; OGLE-III: Udalski et al. 2002). These must target large samples of stars ($\gtrsim 10^5$) to overcome the small probability that a given star will have a planet $\lesssim$10%, that that planet will transit (see above) and that transit will be caught during a given observing campaign. Faint, clustered star fields must be observed to obtain sufficiently large and unconfused samples of stars from the ground. As a result, stars found to have planets are too faint ($V \gtrsim 14$) for further follow-up by other techniques. Transit techniques do, have a clear role in following up planets detected via radial velocities, as the HD 209458 example shows. Detection of transits for this star have constrained *both* the mass and radius of this planet (Henry et al. 2000; Burrows et al. 2000), and have even detected constituents of the planet's photosphere (Charbonneau et al. 2002).

2.5. Gravitational Microlensing

Gravitational microlensing is the focusing (and therefore amplification) of light from background stars by the passage though the line of sight of an intervening object (Pacynski 1986). Because the amplification observed depends on the mass, not the luminosity, of the intervening object, it is well suited to observing intrinsically faint objects like planets. The alignment between the background object, intervening object and observer must, however, be very precise for appreciable brightening to take place[3], which in turn requires that gravitational microlensing searches must target large numbers of candidate background stars

---

[2] For a star of radius R_{star}, planet of radius r_{planet} and planetary orbital semi-major axis $a_{orbital}$, the probability of a system transitting $\propto (R_{star} + r_{planet})/a_{orbital}$

[3] Reviews of the relevant formulae and terminology can be found in Wambsganss (1997); Sackett (1999), Refsdal & Surdej (1994), and Sackett (2004)

https://doi.org/10.1017/S0074180900192915 Published online by Cambridge University Press

($\gtrsim 10^6$). Magnification events due to planets have a reduced probability over those due to their parent stars, but can have large mangitudes and short durations. Several observing programs are currently carrying out intensive observation of lensing events triggered by other programs (in, for example, a search for Galactic dark matter) in a search for low-mass, planetary companions (e.g., PLANET: Dominik et al. 2002; MOA: Bond et al. 2002). To date, no confirmed planetary-mass detections have yet been made. However, gravitational microlensing is statistically very powerful – non-detections in large data sets can be modelled more straightforwardly than, say, non-detections in radial velocity data set. Important conclusions have already been reached by the PLANET team: <30% of stars along the line of sight to the Galactic centre (mostly M-dwarfs) can have Jovian mass planets (Gaudi et al. 2002; Albrow et al 2001).

3. Future Techniques

A common thread emerges from the above – the Earth's atmosphere is a real nuisance. For this reason, most avenues to significantly increased sensitivity involve instruments in space. Unfortunately, everything done in space costs about 100 times more than an equivalent ground-based facility (hence the "Space" entries in the minus columns in Table 1). For planet searching, sadly, spending this money is going to be the only way ahead.

3.1. Astrometry from Space

The HIPPARCOS mission (ESA 1997) delivered astrometry at the ~1 mas level for about 120000 stars – insufficient to detect any of the currently known extra-solar planets, though useful in constraining total masses in some systems. Fig. 1b indicates, however, that real progress will require astrometric precisions at the level of 10-100 μas to detect and characterise planetary systems. A variety of missions targetting sub-mas precision, based on the HIPPARCOS model (i.e., a rotating telescope & all-sky observing) have been proposed:

DIVA: `www.ari.uni-heidelberg.de/diva`
FAME: `www.usno.navy.mil/FAME` [4],
GAIA: `sci.esa.int/home/gaia/`

GAIA is the most ambitious of these missions, and as proposed could potentially detect ~10000 Jovian-mass planetary systems in the 1-10 year period range (Lattanzi et al. 2000).

SIM (Beichman 2004, `sim.jpl.nasa.gov`) is pursuing an alternative pointed observation model. In 2009, it will launch a pair of 0.3 m aperture telescopes, connected to form a 10 m baseline optical interferometer. Over its 5 year mission it will observe a sample of selected stars down to V≈20 obtaining positional accuracies of between 1 and 4 μas – sufficient to detect planets down to Uranus-mass at a distance of 10 pc, or Jupiter-mass at a distance of 100 pc. Neither

[4] The FAME mission was recently cancelled by NASA, though the FAME team continues to explore ways to proceed the mission's goals.

https://doi.org/10.1017/S0074180900192915 Published online by Cambridge University Press

SIM, nor GAIA, however will have the sub-μas accuracies required to detect Earth-mass planets.

3.2. Photometric Transit Detection from Space

The stable photometric conditions provided by a space-based telescope have led to several transit detection missions listed:

Kepler: `www.kepler.arc.nasa.gov`
Eddington: `sci.esa.int/home/eddington`
COROT: `www.astrsp-mrs.fr/projets/corot`

Kepler (Koch 2004) will launch a 1m aperture optical telescope a 12° field of view. It will continuously monitor twenty-one such fields in a patch of sky at 19^h20^m $+37°30'$ over a 4 year period. Because of the diffraction-limited image quality of this telescope, it is able to observe in crowded regions of the sky inaccessible to telescopes on the ground. As such it can target *large numbers* (100 000) of *bright* (V<14) stars. The stars which Kepler finds planets around will be accessible to further study from the ground using other techniques - a critical scientific advantage for a transit detection facility. Moreover, missions like these can detect terrestrial-mass planets, and provide critical information on their frequency around Solar-type stars. Eddington (Favata 2002) will launch post-2008 and pursue similar goals, though over a smaller field-of-view (which means less stars), and will do so over a three year period, following an initial 2 years astroseismology mission. COROT (Baglin et al. 2002) is a smaller mission (0.27 m telescope, launch 2004) which primarily targets astroseismology, but will also perform planet searching observations, primarily targetting Jovian mass planets.

3.3. Direct Detection from Space

Finally, we come to the "Holy Grail" of extra-solar planet detection – direct imaging of Jovian and terrestrial planets around other stars from space. The technical challenges here are staggering, and correspondingly the timelines to missions to carry out these projects are long (launches post-2015+). Nontheless, both ESA (DARWIN: `sci.esa.int/home/darwin`) and NASA (Terrestrial Planet Finder: `planetquest.jpl.nasa.gov/TPF`) have ambitous missions planned. DARWIN has focussed on a "nulling interferometer" concept – light from multiple 1.5 m telescopes will be combined in phase so as to form an interferometer. Baselines of 100 m on such an interferometer can achieve mas resolutions. If the interferometry is done in such a way that the brightest "on-axis" object (i.e., the target star) is combined 180° out of phase, then that light cancels, revealing only the light of any companion objects. This nulling interferometry principle has become a central plank of most space-based interferometers. TPF is also exploring the possibilities for a very large single mirror telescope (giving lower-resolution but larger signal), with advanced optics being used to control scattered light. Both DARWIN and TPF are directly targetting the detection of terrestrial planets – an ambitious goal which ensures they'll find any Jovian mass planets, if present.

These missions, however, propose to not only image these planets, but also to put light from detected planets into spectrographs in a search for detectable biomarkers like CO_2, H_2O and O_3 (see e.g., Meadows 2004). However, even if the enormous challenges these missions face can be surmounted, they will still only be able to target ~150 of the very nearest stars. Current planet detection statistics indicate these systems could contain ~15 gas giant planets, but that the fraction of systems with Solar System-like orbits (ie. nearly circular with no inner gas giants) could be a worryingly smaller number – perhaps as small as zero to three, if we assume the fraction of circular gas giants currently known outside 0.1 AU is representative (Tinney et al. 2002)

4. Conclusions

In the post-2015 era, space missions like TPF and DARWIN will represent the first experiments to directly target biological questions in the astronomical context. In the intervening years, however, a range of important astronomical projects will provide critical information on the frequency of extra-solar gas-giant planets with orbits that look like the gas giants in our own system, the frequency of planetary systems (as opposed to single gas giants), and the frequency with which terrestrial planets occur. Its going to be an exciting time to be a planetary astronomer.

Acknowledgments. My planet searching colleagues – Paul Butler, Geoff Marcy, Hugh Jones, Chris McCarthy, Alan Penny, Brad Carter, Debra Fischer – have significantly informed much of the material above. Indeed most of the insights are theirs. The mistakes are, of course, all my own work.

References

Albrow, M. D., et al. 2001, ApJL, 556, 113

Armstrong, J. T., et al. 1998, ApJ, 496, 550

Baglin, A., et al. 2002, ASP Conf. Ser., 259, 626

Bastian, T. S., Dulk, G. A., & Leblanc, Y. 2000, ApJ, 545, 1058

Battrick, B. 2002, in First Eddington Workshop on Stellar Structure and Habitable Planet Finding, ed. B. Battrick (Noordwijk:ESA)

Beichman, C. 2004, this proceedings

Bond, I. A., et al. 2002, MNRAS, 333, 71

Brown, T. M., & Charbonneau, D. 2000, ASP Conf.Ser., 219, 584

Burrows, A., et al. 2000, ApJ, 534, 97

Butler, R. P., & Marcy, G. W. 1996, ApJ, 464, L153

Butler, R. P., et al. 2002, IAU Symp. 202, in press, see also `www.exoplanets.org/papers.shtml`

Butler, R. P., et al. 2001, ApJ, 555, 410

Charbonneau, D., Brown, T. M., Noyes, R. W., & Gilliland, R. L. 2002, ApJ, 568, 377

Cochran, W. D., Hatzes, A. P., Butler, R. P., & Marcy, G.W. 1997, ApJ, 483, 457

Colavita, M. M., et al. 1999, ApJ, 510, 505

Colavita, M., & Wizinowich, P.L. 2000, Proc. SPIE, 4006, 310,

Dominik, M. 2002, P&SS, 50, 299

ESA 1997, Hipparcos and Tycho Catalogues, ESA SP-1200 (ESA: Noordwijk)

Farrell, W. M., et al. 2004, this proceedings

Favata, F. 2002, in First Eddington Workshop on Stellar Structure and Habitable Planet Finding, ed. B. Battrick (Noordwijk:ESA), 3

Fischer, D. A., et al. 2001, ApJ, 551, 1107

Gaudi, B. S., et al. 2002, ApJ, 566, 463

Glindemann, A. 2001, ESO Messenger, 104, 2

Henry, G. W., Marcy, G. W., Butler, R. P., & Vogt, S. S. 2000, ApJ, 529, 41

Jayawardhana, R. 2004, this proceedings

Koch, D. 2004, this proceedings

Kürster, M., et al. 2000, A&A, 353, L33

Lattanzi, M. G., Spagna, A., Sozzetti, A., & Casertano, S. 2000, MNRAS, 317, 211

Liu, M. C., et al. 2002, ApJ, 571, L519

Luhman, K. L., & Jayawardhana, R. 2002, ApJ, 566, L1132

Marcy, G. W. 2004, this volume

Marcy, G. W., & Butler, R. P. 1996, ApJ, 464, L147

Marcy, G. W., & Butler, R. P. 1998a, ARA&A, 36, 57

Marcy, G. W., & Butler, R. P. 1998b, ASP Conf. Ser., 134, 128

Mayor, M., & Queloz, D. 1995, Nature, 378, 355

Meadows, V. 2004, this proceedings

Nelson, R. P. 2001, in Solar and Extra-Solar Planetary Systems, ed. I. P. Williams & N. Thomas, Lecture Notes in Physics, 577, 35

Noyes, R., et al. 1997, ASP Conf. Ser. 119, 119

Pacynski, B. 1986, ApJ, 301, 503

Pauls, T. A. 2001, IAU Symp. 205, 300

Penny, A., & Collier-Cameron, A. 2002, Occasional Rep. of the ROE, Vol. 17

Perryman, M., 2000, Rep. Prog. Phys., 63, 1209

Refsdal, S., & Surdej, J. 1994, Rep. Prog. Phys., 56, 117

Queloz, D., et al. 1998, ASP Conf. Ser., 134, 324

Sackett, P. 1999, in Planets Outside the Solar System: Theory and Observations, ed. J. M. Marriotti & D. Alloin, NATO-ASI 189-229 (Kluwer:Dodrecht)

Sackett, P. 2004, this volume

Tinney, C. G., et al. 2001, ApJ, 551, 507

Tinney, C. G., et al. 2002, ApJ, 571, 528

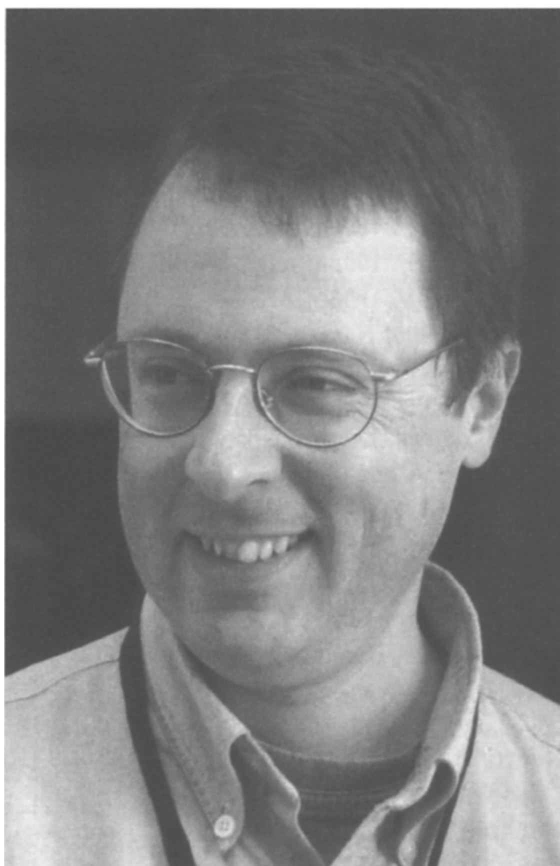
Udalski, A., et al. 2002, A&A, 52, 115

Vogt, S. S., Marcy, G. W., Butler, R. P., & Apps, K. 2000, ApJ, 536, 902

Wambsganss, J. 1997, MNRAS, 284, 172

Wolszcan, A., & Frail, D. A. 1992, Nature, 355, 145

Zarka, P., Treumann, R. A., Ryabov, B. P., & Ryabov, V. B. 2001, Ap&SS, 277, 293



Chris Tinney (*photo: Seth Shostak*)

https://doi.org/10.1017/S0074180900192915 Published online by Cambridge University Press