A free-floating planet population in the Galaxy?

Hans Zinnecker
Astrophysikalisches Institut Potsdam, An der Sternwarte 16, D-14482 Potsdam, Germany (hzinnecker@aip.de)

Abstract. Most young low-mass stars are born as binary systems, and circumstellar disks have recently been observed around the individual components of proto-binary systems (e.g. L1551-IRS5). Thus planets and planetary systems are likely to form around the individual stellar components in sufficiently wide binary systems. However, a good fraction of planets born in binary systems will in the long run be subject to ejection due to gravitational perturbations. Therefore, we expect that there should exist a free-floating population of Jupiter-like or even Earth-like planets in interstellar space. There is hope to detect the free-floating Jupiters through gravitational microlensing observations towards the Galactic Bulge, especially with large-format detectors in the near-infrared (e.g. with VISTA or NGST), on timescales of a few days.

1. Speculation of Existence

Observations over the past decade have shown that most young low-mass stars are born as binary systems (e.g. Mathieu 1994, Mayor et al. 2000). Furthermore, circumstellar disks have recently been observed around the individual stellar components of protobinary systems (e.g. L1551-IRS5, Rodriguez et al. 1998; HK Tau, Menard & Stapelfeldt 2000). Thus, planets and planetary systems are likely to form around the individual components in sufficiently wide binary systems. A case in point is 16 Cygni, where a Jupiter-like companion has been detected around component B by radial velocity measurements (Cochran et al. 1996).

Here we speculate that a good fraction of planets born in binary systems will be subject to dynamical ejection due to gravitational perturbations resulting from periapsis passages of the stars revolving around each other, typically in rather eccentric orbits. Therefore we expect a population of ejected and thus free-floating planets to exist in the Galactic Disk – and maybe in the Galactic Halo as well, as the frequency of wide visual binaries (separations > 30 AU) seems to be at least as high for halo stars as for disk stars (Köhler et al. 2000).

---

1 Contributed talk, presented at “Microlensing 2000”, Cape Town (Feb. 2000), in press

2 Although the case of TMR-1C (Terebey et al. 2000) did not turn out to be a young planet being ejected, some young multiple systems appear to eject very low-mass objects (Reipurth 2000).
2. Caveat

To be fair, there are also arguments against our speculation. For example, planet formation may be inhibited by the mutual spiral shocks induced in the respective circumstellar disks which will heat the disk gas and dust (Nelson 2000). This might cause the dust grains to evaporate and be destroyed, certainly the ice mantles if not the silicate cores too, depending on the shock temperature (higher/lower than 1500K). Thus grain growth and the collisional build-up of planetesimals will be prevented. Similarly, direct gravitational instability of the gas disk (another possibility to form a giant Jupiter-like planet) is impeded, if the disk is too hot (the Toomre Q parameter exceeds unity for too large a sound speed or gas temperature, even if the disk surface density is high). Finally, the Goldreich-Ward (1973) instability of a cold thin dust disk, even if it operated in a circumstellar disk around a single star, may not do so in the respective disks around binary star components, as the dust may never settle into the disk’s midplane in a binary star+disk system.

While these qualitative arguments against planet formation in binary systems must be further investigated and while a lot of uncertainty remains, it is nonetheless worthwhile to proceed on the assumption that some planet formation occurs even in binary systems, especially in those which are wider than a critical separation of the stellar pair, which we take to be the separation where the mode of the semi-major axis distribution occurs – 30 AU according to Duquennoy & Mayor (1991). That is, we assume that 50% of all low-mass binaries can indeed form planets (cf. Marzari & Scholl 2000).

3. Prospects for Detection

Next we evaluate the prospects for detecting a population of Jupiter-mass free-floating planets towards the Galactic Bulge (Center). We also bracket our estimates by considering objects a factor of 10 more massive (i.e. minimum mass brown dwarfs) and a factor 10 less massive (maximum mass of Earth-type planets). We consider planets associated with stars below 1 \( M_\odot \) (with main sequence lifetimes exceeding the age of the Galaxy). We assume 50% binary frequency for these low-mass stars, half of which we expect to form planets. Each planet forming binary system is assumed to form 4 planets, two around each component, on average. Finally we assume that one of the two planets per stellar component is eventually ejected.

The number density of low-mass stellar systems in the solar neighborhood is \( n_s = 0.1 \) per pc\(^3\). Thus, under the above assumption, the number density of free-floating planets (Jupiters) will be \( n_p = 0.05 \) per pc\(^3\). Then the surface density of free-floating planets towards the Galactic Center will be of order \( N_p = 10^3 \) pc\(^{-2}\), assuming a distance to the Galactic Center of 10 kpc and an average stellar density in the inner Galaxy 2 times higher than in the local Solar Neighborhood.

Now, the probability \( P \) (also sometimes called the “optical depth”) for a microlensing occurrence is given by the following area coverage factor

\[
P = \pi \times R_{E,p}^2 \times N_p
\]
where $R_{E,p}$ is the Einstein radius of the planet ($R_{E,p} = \sqrt{\frac{4GM_pD_sx(1-x)}{c^2}}$, with $D_s$ being the distance to the source population, here of order 10 kpc; and $x=D_L/D_s$, the ratio of the distance of the lens population to the source population, typically $x=0.5$).

When normalized to $M_{J_{up}} = 10^{-3} M_\odot$ and for $x=0.5$, numerically this turns out to be

$$R_{E,p} = 10^{12.5} \times \sqrt{\frac{M}{M_{J_{up}}}} \text{ cm.}$$

Hence

$$P = 3 \times 10^{-9} \times (\frac{M}{M_{J_{up}}})$$

is a reasonable estimate for the “optical depth” due to free-floating planets of mass $M$ towards the inner Galaxy.

The timescale for Einstein ring crossing, i.e. the half-width of the lightcurve of the source magnification, is given by

$$t = \frac{R_{E,p}}{v}$$

where $v \sim 200 \text{ km/s}$ is the relative speed of the observer with respect to the lens.

One finds

$$t = \frac{10^{12.5}}{10^{7.3}} \text{ sec} = 1.5 \times 10^5 \text{ sec} \sim 2 \text{ days}$$

### 4. Detection Requirements

The above numbers translate into the following detection requirements: to detect a microlensing event due to free-floating Jupiters in the inner Galaxy we need to observe some $3 \times 10^8$ stellar objects in the Galactic Bulge for a few days, with a time resolution of hours. This is difficult but not impossible. For example, the VST 2.5m telescope to be installed on Paranal/Chile in 2002 with its 1 degree field-of-view in very good seeing (0.4 arcsec) corresponds to $\sim 10^8$ pixels, and may thus be able to realistically resolve some $10^7$ point sources down to the confusion limit in the far-red bands (10 pixels per object). Therefore some 30 fields of 1 degree must be monitored each night. The VISTA telescope, a 4m mirror on Paranal with a 1 degree field-of-view for infrared (JHK) observations, will be even better (first light in 2005) because in the near-infrared we can penetrate the dust towards the Galactic Center, providing a higher and fainter source surface density. Thus the confusion limit will be reached more quickly and 30 fields can actually be monitored once or twice per night (good sampling). Finally, it is conceivable that the Next Generation Space Telescope (NGST), to be launched in 2009, will be able to do the job, as it will mostly operate in staring mode and always at the diffraction limit (60 mas). Its field-of-view is around 4 arcmin (8k x 8k detectors with 30 mas pixels), corresponding to $10^{7.5}$ pixels. Due to the much higher spatial resolution compared to VISTA, the NGST will reach a fainter confusion limit than VISTA within a short exposure time.
(a few seconds, or tens of seconds, depending on the precise galactic longitude and latitude) and will likely resolve $10^{6.5}$ point sources. It then ‘just’ needs 100 such short exposures of the same field, sampled at intervals of a few hours, in order to monitor three hundred million objects for a microlensing variability of a few days, thus finding out if the predicted microlensing by free-floating Jupiters occurs. If so, this would herald a new class of objects in interstellar space.

PS. Microlensing constraints on the frequency of Jupiter-mass planets in orbit around low-mass stars with separations of 1.5 to 3 AU (the lensing zone) were analyzed by the PLANET collaboration. No clear signatures of such planets among 100 microlensing events have been detected, implying a frequency of less than 33% (Gaudi et al. 2000, these Proceedings). Bound Jupiters in wider orbits (wider than 1.5 Einstein radii or about 5 AU for a solar-mass lens) are much harder to distinguish from free-floating Jupiters, with only a small fraction of microlensing events still carrying a weak signal of the parent star (cf. DiStefano & Scalzo 1999; Gaudi, priv. comm.).

5. Acknowledgement

My first attempt to estimate the number of free-floating planets ejected from binary systems and their detection by gravitational microlensing goes back to a young binary stars workshop in Stony Brook 1996. Since then, I benefitted enormously from the expertise of my colleague Joachim Wambsganss to whom I owe both my increasing interest and increasing knowledge of gravitational microlensing. I am also grateful to Rosanne DiStefano for insightful discussions.

References

Cochran, Hatzes, Marcy & Butler 1996, BAAS 28, 1111
DiStefano & Scalzo 1999, ApJ. 512, 564
Duquennoy & Mayor 1991, A & A 248, 485
Gaudi et al. 2000, astro-ph/0004269
Goldreich & Ward 1973, ApJ. 183, 1051
Köhler, Zinnecker, & Jahreiss 2000, in Birth and Evolution of Binary Stars (Poster Proc. IAU-Symp. 200), eds. Reipurth & Zinnecker, p. 148
Marzari & Scholl 2000, ApJ. 543, 328
Mathieu 1994, ARAA 32, 465
Mayor et al. 2000, in The Formation of Binary Stars, IAU Symp. 200, eds. Zinnecker & Mathieu, ASP Conf. Series, in press
Menard & Stapelfeldt 2000, in The Formation of Binary Stars, IAU Symp. 200, eds. Zinnecker & Mathieu, ASP Conf. Series, in press
Nelson 2000, ApJ. 537, L65
Reipurth 2000, in The formation of Binary Stars, IAU Symp. 200, eds. Zinnecker & Mathieu, ASP Conf. Series, in press
Rodriguez et al. 1998, Nature 395, 355
Terebey et al. 2000, A.J. 119, 2341