Planets of young stars

Eike W. Guenther and Massimiliano Esposito

Thüringer Landessternwarte Tautenburg, 07778 Tautenburg, Germany

Abstract.

Since the first massive planet in a short period orbit was discovered, the question arised how such an object could have formed. There are basically two formation scenarios: migration due to planet-disk or planet-planet interaction. Which of the two scenarios is more realistic can be found out by observing short-period planets of stars with an age between $10^7$ and $10^8$ yrs. The second aim of the survey is to find out how many planets originally formed, and how many of these are destroyed in the first Gyrs: Do most young, close-in planets evaporate, or spiral into the host stars? In here we report on the first results of a radial-velocity search program for planets of young stars which we began in 2004. Using HARPS, we currently monitor 85 stars with ages between $10^7$ and $10^8$ yrs. We show that the detection of planets of young stars is possible. Up to now, we have identified 3 planet-candidates. Taking this result together with the results of other surveys, we conclude that the frequency of massive-short period planets of young stars is not dramatically higher than that of old stars.

1. The idea for the survey

In the last 11 years, about 200 extrasolar planets have been detected indirectly by means of precise radial velocity (RV) surveys. The detection of now 16 transiting planets, as well as astrometric observations of $\epsilon$ Eri and the detection of the thermal emission of $\mu$ Andromeda b with the Spitzer satellite demonstrates that the vast majority of the objects found by RV-surveys are in fact planets (Charbonneau et al. (2000); Harrington et al. (2006); Benedict et al. (2006)). The orbits of the extrasolar planets are surprisingly different from those in our solar system, as most of the long-period planets have rather eccentric orbits, and as there are planets with very short orbital periods (so called “hot Jupiters”, or “Pegasides” after the first such object found.). Up to now 49 extrasolar planets have been found which have a semi-major axis of $\leq 0.1$ AU (orbital periods $\leq 10$ days). When corrected for selection effects, the true frequency of hot Jupiters orbiting old stars is few % (Lineweaver & Grether, (2003)).

The discovery of hot Jupiters was very surprising, and their formation still poses a mystery. In the standard model massive planets form via core accretion: In the first step a solid core of about 5 to 10 $M_{\rm earth}$ forms, which subsequently accretes gas from the disk in order to form a $M_{\rm Jupiter}$-planet (see for example the review on planet formation by Perryman (2000)). The core accretion model is supported by the discovery of the eclipsing planet HD149026 b which has a $\sim 67 M_{\rm earth}$ core consisting of heavy elements (Sato et al. 2005), and by the fact that stars with an overabundance of heavy elements also have a higher frequency...
of massive planets (Santos et al. 2004). In-situ formation of 'hot Jupiters' is unlikely, as it requires a large surface density of dust particles in the inner disk. Such large surface density of dust particles is considered unlikely, because the temperature in the inner 0.1 AU of the disk is above the sublimation temperature of the dust. Interferometric observations of young stars in fact show that there is basically no dust within 0.1 AU of the star (Akeson et al. 2005). With in-situ formation being unlikely, there are only two scenarios for the formation of close-in planets:

1.) **Planet migration via interaction with the disk:** Giant planets in a circumstellar disk can migrate inwards by torques between the planet and the disk. The migration-rate due to interaction with the disk is over large range independent of the mass of the planet but depends linearly on the mass of the disk (Lufkin et al. 2004). In general migration will damp the eccentricities so that even young close-in planets should have round orbits. In this scenario 7% of the stars should have planets of more than 0.6 $M_{\text{jupiter}}$ within 0.1 AU at the end of the formation period (age $10^7$ to $10^8$ yrs; Armitage et al. 2002). However, as shown by D’Angelo et al. (2006) this picture changes dramatically, if an eccentric disk is considered. A planet in an eccentric disk will also have an eccentric orbit, and the eccentricity of the planet will even increase with time. If the eccentricity becomes larger than 0.2 the planet will migrate outward instead of inward.

2.) **Migration due to planet-planet interaction:** If a system of three or more giant planets forms, their orbits are stable during their formation epoch ($\leq 10^7$ yrs). But, after the depletion of the disk gas, mutual gravitational perturbation between the planets will induce a gradual increase in their orbital eccentricities, until their orbits become unstable. Subsequent gravitational encounters among these planets can lead to the ejection of the planets from the system while placing others into highly eccentric orbits, both closer and farther from the star (Weidenschilling & Marzari 1996). In this scenario, the close-in planets form at an age of about $10^7$ yrs, and the orbits will initially be eccentric. After $10^8$ yrs the orbits of short-period planets will be round due to tidal interaction.

In order to find out which of the two scenarios is more realistic, we have to observe stars with ages between $10^7$ to $10^8$ yrs. In the case of the first scenario about 7% of the stars will have a hot Jupiter with a round orbit. In the case of the second scenario, the interaction between planets would happen at an age between $10^7$ to $10^8$ yrs. If the second model were correct, we may find planets in unstable orbits. At least we should find close-in planets with eccentric orbits.

Another interesting aspect of our project is that we can find out how many planets originally formed, and how many of them are destroyed within the first Gyrs. There are several possibilities how planets can be destroyed even after the protoplanetary disks have been dispersed. Close-in extrasolar planets experience strong tidal interactions with their central star. If the planet’s orbital period is shorter than the star’s rotation period, tidal friction will lead to a spin-up of the star and, thus also lead to a decrease of the semi-major axis of the planet’s orbit (Pätzold et al. 2004). It is thus in principle possible that planets may even spiral into the host star. Close-in planets may also evaporate due to the XUV radiation of the star. It has been estimated that planets with an orbital
distance $\leq 10$ days ($\sim 0.1$ AU) loose between 20 first Gyrs, were the XUV flux of the host star is particularly strong (Baraffe et al. 2006). If this is true, all hot Neptunes orbiting old stars would have been short period Jupiters at young age, and we should find many massive, close-in planets in our survey.

2. The survey

For our survey, we selected 92 stars in the TWA Hydra [10-30 Myr], $\beta$ Pic [$\sim 12$ Myr], Horologium [10-30 Myr], Tucana [\sim 40 Myr], IC2391 [30-40 Myr] association and a few stars of similar age in the field. We were surprised to find out that 7 of the stars selected from the literature turned out to be old, as they have no LiI-absorption, and the RV-variations are $\leq 5 \, m \, s^{-1}$.

The survey is being carried out with HARPS on the ESO 3.6-m-telescope at La Silla, started in 2004 and is still ongoing. Up to now, we have taken 558 spectra of the 85 young stars. We use the ThAr-simultaneous reference method and the RV-pipeline developed by the Geneva group (Mayor et al. 2003). All observations were carried out in service mode and spectra were taken at random time during the semester.

3. The influence of stellar activity

Of course young stars are less ideal for RV-planet-search-projects, because they are active. The question thus is, whether it is possible to detect close-in massive planets, or not. Previous to this survey, we have carried out RV-measurements of classical and weak-line T Tauri stars. We found that 50% of the stars show RV-variation of $\leq 750 \, m \, s^{-1}$, and that the RV-jitter can be as large as 2 or 3 $km \, s^{-1}$ (Fig. 1). This limits the possibility to detect companions with orbital periods of 10 days to masses that are in the brown dwarf regime. Thus, the detection of planets of T Tauri stars by means of precise RV-measurements is extremely difficult, if not impossible. In the case of the stars with an age between $10^7$ to $10^8$ yrs, we find that more than 50% of the stars show RV-variations of $\leq 100 \, m \, s^{-1}$. This allows us to detect planets with the mass of Jupiter with orbital periods of $\leq 10$ days.

For detecting planets of active stars, it is necessary to carry out a number of tests in order to demonstrate that the RV-variations are caused by an orbiting planet and not by stellar activity. In principle, the spectral-lines of a spotted star are red-shifted, when the spot rotates into view, and blue-shifted when the spot rotates out of sight.

- A spot on the stellar surface will cause a hump in the line-profile. In a spotted star the line-asymmetry will thus be correlated with the RV.

- Spots on the stellar surface will cause brightness variations. In a spotted star the brightness variations are thus related to the RV-variations.

- Plage regions on the sun appear bright in images taken in the emission core of the Ca II H and K-lines. Thus, the presence and absence of active regions on the stellar surface can be inferred from the strength of the
emission cores of these lines. In a spotted star, the emission cores are thus correlated with the stellar activity. Other chromospheric lines like H\(\alpha\) may also be used for similar purposes.

- Spots have a limited life time. The RV-signal of spotted star thus changes with time. However, we should keep in mind that there are some stars were the spot-pattern remained unchanged for years.

- Since the difference in brightness between a spot and the photosphere is much smaller in the infrared than in the optical regime, the RV-variations of a spotted star is much smaller at infrared wavelength than in the optical.

4. Binaries

The first companions found were stellar companions. In the following, we will give a short overview of the binaries found.

**HD113449:** We have taken 14 RV-measurements of this star which is a member of the AB Dor moving group (Zuckerman, 2004) and found that it to be a binary with an orbital period of 221 days. The m sin\(^\circ\) of the companion is about half a solar-mass.

**HD35850:** Although we have taken only 4 spectra of this star, the large RV-variations indicate that it must be a binary, possibly of short period. This star is member of the \(\beta\) Pic moving group (Zuckerman & Song, 2004).

**V343Nor:** We have taken 14 RV-measurements of this star, and found a linear trend of 1.7 \(\pm\) 0.1 km s\(^{-1}\) year\(^{-1}\). It thus must be a binary with a long orbital period.
5. A very interesting candidate

Amongst the 85 young stars surveyed, we found three stars which show RV-variations with amplitudes between 200 and 400 m s\(^{-1}\) and periods of a few days. One of these is particularly interesting: We observed this for 1.3 years, and found only one very clean period of 5.02 days (Fig. 2). The RV-values also phase up very nicely with this period (Fig. 3). Thus, the RV-variations must either be caused by a long-lived active region, or by an orbiting object with an \(m \sin i\) of 0.8 \(M_{Jupiter}\). Active regions of stars usually change within a year, and thus the periodogram of active stars usually does not look as clean as Fig. 2 (see König et al. (2005) for details). However, there are stars were the spot-pattern did not change in years. For example in the case of V410 Tau, the spot pattern remained unchanged for 10 years (Fernández et al. 2004; Stelzer et al. 2003)! In order to find out whether the RV-variations are caused by stellar activity, or by an orbiting planet, we thus have to undertake all the tests mentioned above. The outcome of the first test is shown in Fig. 4. The figure shows the normalised equivalent width of the CaH, CaK, H\(\alpha\), H\(\beta\), and H\(\gamma\) emission lines phased to the 5.02 day period. The equivalent widths of the lines certainly do not phase up with this period. We are currently carrying out photometric observations and measuring the line-asymmetry. More work still needs to be done until a definite conclusion can be drawn but up to now this candidate looks promising. The best, and most critical test will be to carry out RV-measurements at infrared wavelengths.

6. Putting things in perspective

Additionally to this survey we have also carried out a similar survey in the northern hemisphere using the 2-m-Alfred Jensch telescope in Tautenburg. In that survey we observed 46 young stars (Esposito et al. 2006). Most of the stars in that observed have ages comparable to the Pleiades (~ 100 Myr) but some are 300 ÷ 500 Myr old. In that survey we found only one good candidate. The period of the RV-variations of this object is only 1.3 days, and the amplitude 51 m s\(^{-1}\). For 19 stars we can exclude planets with an \(m \sin i \geq 1 \ M_{Jupiter}\) and with periods \(\leq 10\) days. For 8 additional stars it is possible exclude planets with an \(m \sin i \geq 5 \ M_{Jupiter}\), and periods \(\leq 10\) days. Thus, in total, we have served 131 young stars, and found only 4 good planet candidates. Up to now, we can not say whether any of these is really a planet but we can already conclude that there is certainly not a large population of close-in massive planets. This implies
E. Guenther, M. Esposito

Figure 2. Periodogram of the RV-variation of our best candidate. There is only one significant period.

Figure 3. RV-variations phased to a period of 5.02 days. Since we monitored the star for 1.3 years, the periodic RV-variations must either be caused by a very stable active region, or by an orbiting planet.

that the fraction of close-in planets that are destroyed, or evaporate in the first $10^7$ to $10^9$ yrs is low. This result is in good agreement with other studies:

Paulson & Yelda (2006) observed the β Pic (∼12 Myr) association, IC 2391 (30-40 Myr), the Castor moving group, and the Ursa Major association (∼300
Figure 4. In order to find out whether the RV-variations are caused by stellar activity, or by an orbiting planet, we determined the equivalent width of all the chromospheric lines. The figure shows the normalised equivalent widths of the CaH, CaK, Hα, Hβ, and Hγ emission lines phased to the same period as above. From the lack of correlation, we conclude that the RV-variation are unlikely to be caused by stellar activity.

Myr), as well as stars of similar age in the field, 61 stars in total. They can rule out companions of these stars with a mass of more than one $M_{Jupiter}$ and an orbital period shorter than 6 days. Paulson et al. (2004) also monitored 98 stars in the Hyades (age $\sim$ 700 Myr). They found four stars with periodic RV-variations but after monitoring these stars photometrically, they could rule out in three of the four stars that the RV-variations are caused by orbiting planets.

Taking everything together, we can thus conclude that the frequency of massive-short period planets of young stars is not dramatically higher than that of old stars. It thus seems unlikely to us that the vast majority of the massive, short-period planets are destroyed in the first $10^7$ to $10^9$ yrs.

Acknowledgments. We are grateful to the user support group of ESO/La Silla. This research has made use of the SIMBAD database, operated at CDS, Strasbourg, France.

References

Akeson R.L., Walker, C.H., Wood, K., Eisner, J.A., Scire, E., Penprase, B., Ciardi, D.R., van Belle, G.T., Whitney, B., & Bjorkman, J.E. 2005, ApJ, 622, 440
Armitage Ph. J., Livio, M., Lubow, S.H., & Pringle, J.E. 2002, MNRAS, 334, 248
Baraffe, I., Alibert, Y., Chabrier, G., & Benz, W. 2006, A&A, 450, 1221
Benedict, G. F., McArthur, B. E., Gatewood, G., Nelan, E., Cochran, W. D., Hatzes, A., Endl, M., Wittenmyer, R., Baliunas, S.L., Walker, G.A.H., Yang, S., Kürster, M., Els, S., & Paulson, D.B. 2006, AJ, 132, 2206
Charbonneau, D., Brown, T.M., Latham, D.W., & Mayor, M. 2000, ApJ, 529, L45
D’Angelo, G., Lubow, St.H., & Bate, M.R. 2006, ApJ, 652, 1698
Esposito, M., Guenther, E., Hatges, A.P., & Hartmann, M. 2006, Tenth Anniversary of 51 Peg-b: Status of and prospects for hot Jupiter studies, L. Arnold, F. Bouchy and C. Moutou. (eds.), Published by Frontier Group, Paris, p.127 (astro-ph/0510436)
Fernández, M., Stelzer, B., Henden, A., Grankin, K., Gameiro, J. F., Costa, V. M., Guenther, E., Amado, P. J., & Rodriguez, E. 2004, A&A, 427, 263
Harrington, J., Hansen, B.M., Luszcz, S.H., Seager, S., Deming, D., Menou, K., Cho, J. Y.-K., Richardson, L. J. 2006, Sci 314, 623
König, B., Guenther, E.W., Woitas, J., & Hatges, A. P., 2005, A&A, 435, 215
Lineweaver, Ch.H. & Grether, D. 2003 ApJ, 598, 1350L
Lufkin, G., Quinn, T., Wadsley, J., Stadel, J., & Governato, F. 2004, MNRAS, 347, 421
Mayor, M., et al. 2003, The Messenger 114, 20
Pätzold, M., Carone, L., & Rauer, H. 2004, A&A, 427, 1075
Paulson, D.B., Saar, S.H., Cochran, W.D., & Henry, G.W. 2004, AJ, 127, 1644
Paulson, D.B., & Yelda, S. 2006, PASP, 118, 706
Perryman, M.A.C. 2000, Reports of Progress in Physics, 63, 1209
Santos, N. C., Israelian, G., & Mayor, M. 2004, A&A, 415, 1153
Sato, B., et al. 2005, ApJ633, 465
Stelzer, B., Fernández, M., Costa, V. M., Gameiro, J. F., Grankin, K., Henden, A., Guenther, E., Mohanty, S., Flaccomio, E., Burwitz, V., Jayawardhana, R., Predehl, P., & Durisen, R.H., 2003, A&A, 411, 517
Weidenschilling, S.J., & Marzari, F. 1996, Nat, 384, 619
Wichmann, R., Schmitt, J. H. M. M., & Hubrig, S. 2003, A&A, 399, 983
Zuckerman, B., & Song, I. 2004, ARA&A, 42, 685
Zuckerman, B., Song, I., & Bessell, M.S., 2004, ApJ, 613, 65