# Constraints on Extrasolar Planet Populations from VLT NACO and MMT Direct Imaging Surveys (submitted to ApJ)


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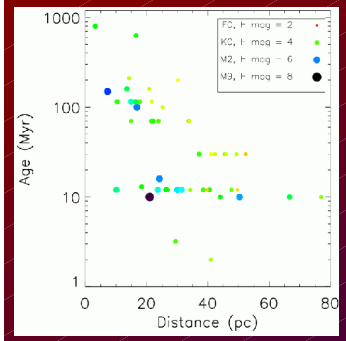


Figure 1: The 60 target stars observed in the Biller et al. 2007 and Masciadri et al. 2005 surveys, with age and distance given, and the size and color of the points representing absolute H magnitude as a proxy for spectral type. Most of the targets belong to one of the following associations: TWA (10 Myr), Beta Pic (12 Myr), Tuc/Hor (30 Myr), AB Dor (70 Myr), or Her/Lyra (115 Myr). The remaining ages are found by $R'_{HK}$ or Lithium measurements

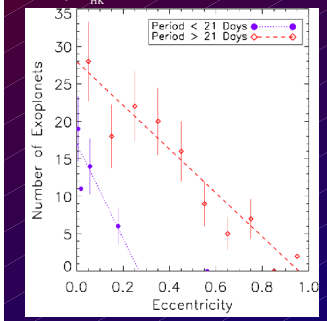


Figure 2: Assumed distributions of exoplanet eccentricities, with Hot Jupiters separate, with the histogram of known radial velocity planets.

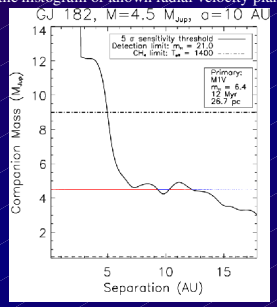


Figure 3: Simulated planets, all with mass and semi-major axis of 4.5 $M_{Jup}$ and 10 AU, and eccentricity distribution given by Fig. 2, against the measured 5σ contrast curve for this target star, GJ 182. Blue points are detected planets, red points go undetected

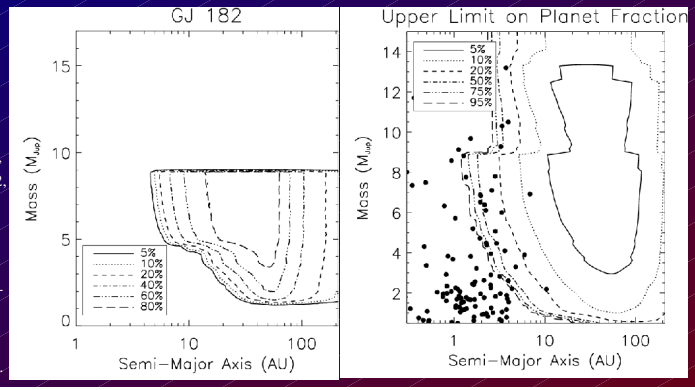


Figure 4: The full completeness plot for GJ 182, with a grid of mass and semi-major axis evaluated as in Fig. 3. Within the inner contour, if such a planet existed, we would have an 80% chance of detecting it.


*Abstract: We examine the implications for the distribution of extrasolar planets based on the null results from two direct imaging surveys. Combining the measured contrast curves from 12 stars observed with the VLT NACO adaptive optics system by Masciadri et al. 2005, and 48 stars observed with the VLT NACO and MMT SDI devices by Biller et al. 2007, we consider what distributions for planet mass and semi-major axis can be ruled out by these data. We can set a 1σ upper limit of 5% on the fraction of stars that host planets with semi-major axis between 20 and 80 AU, and mass above 4 $M_{Jup}$. Also at the 1σ level we can rule out a power-law distribution for semi-major axis with index 0 and upper cut-off of 13 AU, and index -0.5 with an upper cut-off of 27 AU. We cannot, however, with our current observations, place any constraints on the model suggested by the current radial velocity planets, a power law of index -1, nor can we rule out the models of Ida & Lin 2004 for the masses and semi-major axes of giant planets.*


As high-contrast imaging surveys are currently underway searching for self-luminous giant planets around young, nearby stars, it is important to consider what statistical results can be drawn from null results when no planets are detected. Using the measured contrast curves of 60 young, nearby target stars from the surveys of Biller et al. 2007 and Masciadri et al. 2005 (information on the targets is given in Fig. 1), we run a series of Monte Carlo simulations to evaluate which planets could be detected with our observations, and which could not. Each simulated planet is given an inclination angle, longitude of the ascending node, and mean anomaly, as well as an eccentricity based on a distribution consistent with known radial velocity planets (using data from the Catalog of Nearby Exoplanets, exoplanets.org), as shown in Fig. 2. Then, for a given mass and semi-major axis of the planet, we can calculate the separation on the sky between the target star and each planet, given the distance to the star. We convert planet mass into H-band luminosity using the models of Burrows et al. 2003, and then compare our simulated planets to the observed 5σ contrast curve for that target star (Fig. 3). The fraction lying above the curve (as well as above the lower flux limit and below the methane limit for stars observed using SDI from Biller et al. 2007– a planet that is too hot will not have a strong methane band, and so Simultaneous Differential Imaging using filters centered on the 1.65 micron methane feature will not be as effective) represents the detection completeness of the observation for planets for the given target star. Running these simulations for a grid of mass and semi-major axis, as in Fig. 4, gives a completeness plot for a particular star, showing the ability to detect planets of various parameters with the given observations. In Fig. 5, we combine these completeness plots for all our target stars, and give the upper limit on the fraction of stars that can have planets with the given parameters. Within the inner contour, we'd expect to detect 20 planets if each star had a planet of that mass and semi-major axis; since we detect none, the 1σ upper limit on the planet fraction is 5%.

We also consider models with power-law distributions for mass and semi-major axis. We adopt the power law index of Butler et al. 2006, as fit to known radial velocity planets, for planet mass (see Fig. 6), and consider various values of the index and upper cut-off to a power-law distribution for semi-major axis. In Fig. 7 we show the results of a Monte Carlo simulation, again for the target star GJ 182, for a power law of index -0.5 and upper cut-off of 40 AU. In this case, we could detect about 13% of the simulated planets. By combining this detection percentage with the normalization of Fischer & Valenti 2005 (which gives a planet fraction of about 5% for planets within 2.5 AU and more massive than 1.6 $M_{Jup}$ for FGK stars, though we apply the result to the M stars in our survey as well) we can examine our null result with respect to the number of planets expected to be detected by various models. In Fig. 8 and 9, we consider a variety of power-law indices and upper limits to the semi-major axis distribution, ruling out most models with positive power law index, and placing constraints on how far a distribution with power law index -0.5 can extend. Finally, we examine the core accretion models of Ida & Lin 2004, but since these predict between 0.6 and 0.9 detected planets, we cannot place any constraints on these models.


References:
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Butler et al. ApJ 646, 2006.
Burrows et al. ApJ 596, 2003.
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Ida & Lin ApJ 604, 2004
Fischer & Valenti ApJ 622, 2005.
Masciadri et al. ApJ 625, 2005.



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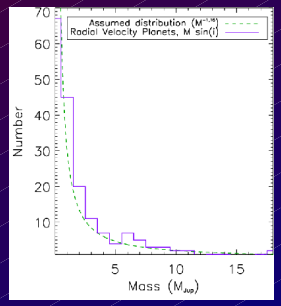


Figure 6: The assumed power-law distribution for masses of planets, as given by Butler et al. 2006. The histogram of known radial velocity planets is also shown.

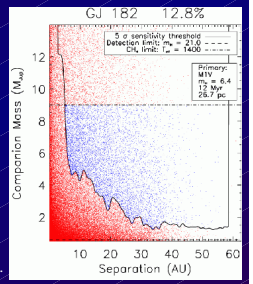


Figure 7: Simulated planets around the star GJ 182, with mass given as in Fig 6, eccentricity as in Fig. 2, and semi-major axis as a power-law with index -0.5, cut off at 40 AU. About 13% of the simulated planets can be detected.

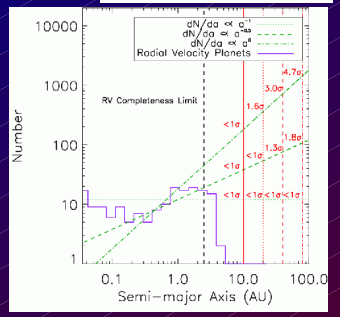


Figure 8: Various power-law distributions for semi-major axis, plotted against known radial velocity planets. Green lines show the power laws, and red lines the upper cut-offs. At each intersection is the confidence with which we can rule out that model, given the null result of our survey.

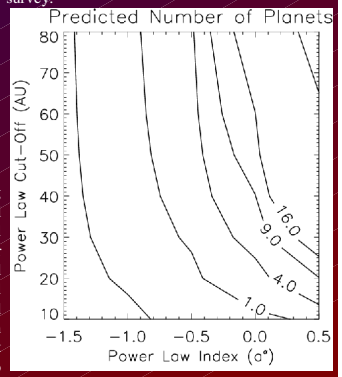


Figure 9: Contour plot showing the number of planets we'd expect to detect given a model for semi-major axis of a power law with the given index and upper cut-off. From our null result, we can place solid contraints on models with positive power law indices, but our data are insufficient to address the possibility of more negative indices. The leftmost and rightmost contours represent 0.1 and 100 predicted planets, respectively.