AMERICAN MUSEUM OF NATURAL HISTORY

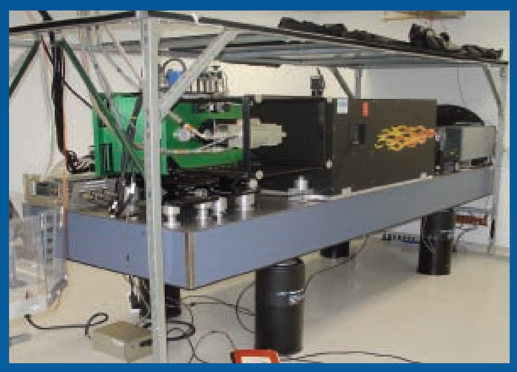
THE LYOT PROJECT

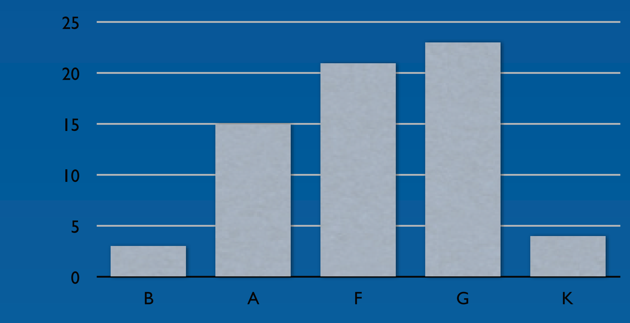
Survey Statistical Analysis

Jérémy Leconte (ENS Paris), Rémi Soummer, Ben R. Oppenheimer, Sasha Hinkley (Columbia)
Douglas Brenner, Anand Sivaramakrishnan, Jeffrey R. Kuhn (University of Hawaii),
Marshall Perrin (UC-Berkeley), Lewis C. Roberts, Jr (Boeing), James Graham (UC-Berkeley),
Michal Simon (Stony Brook), Robert A. Brown (STScI), Gilles Chabrier (CRAL), Isabelle Baraffe (CRAL)

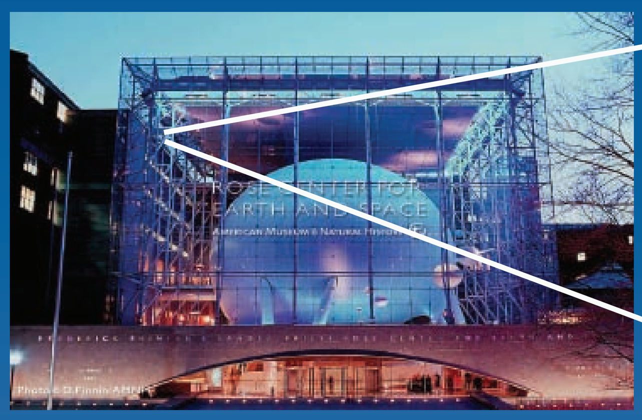
Abstract:

Our Lyot Project survey has observed 66 stars to date. We have developed tools to reduce speckle noise with Angular Differential Imaging, to estimate the detection sensitivity (dynamic range) from the data, and to analyze the population of possible companions by Monte Carlo and statistical methods. Most of the observations of individual targets did not detect a companion. Since null results can be as important as detections, we analyzed each observation to determine the characteristics of the companions that escaped detection in order to constrain upper limits on the companion frequency.



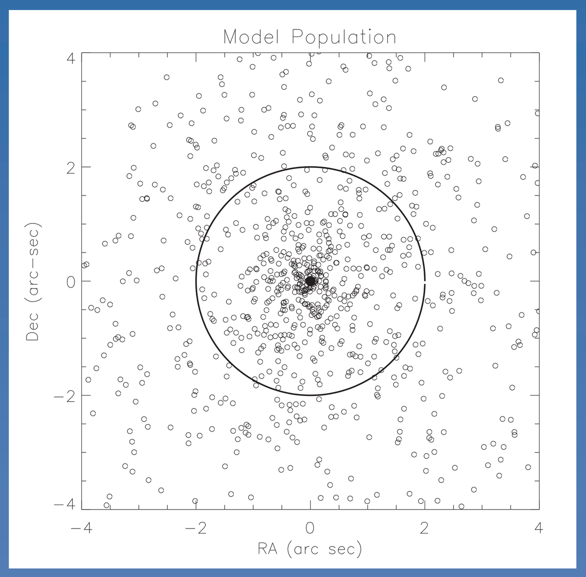


Spectral types of the targets



The Lyot Project near-IR Coronagraph:

The Lyot Project is a multi-institution project based in the Department of Astrophysics at the American Museum of Natural History (AMNH). We use a combination of high-order adaptive optics (AO) and coronagraphy operating at the diffraction limit to suppress the starlight which overwhelms faint companions. We use an optimized Lyot coronagraph which is located at the 3.63m Advanced Electro-Optical System, which is operated by the US Air Force in Maui, Hawaii. This system uses a Shack-Hartmann wavefront sensor and a 941 actuator deformable mirror, and has the potential for some of the highest quality AO images possible today (with Strehl Ratios between 60 and 90). The Lyot Project has observed 66 stars since its commissionning run in March 2004. The star list is composed of nearby stars (<25pc) in which there are stars with known planets (7), disks (9), and younger than 1GYr (19). Most of the stars are F and G spectral types (see histogram above). The last run is scheduled for June 2007. The coronagraph will be decommissioned after this and upgraded with an integral field spectrograph (Project 1640) for use at the Palomar 5m telescope.



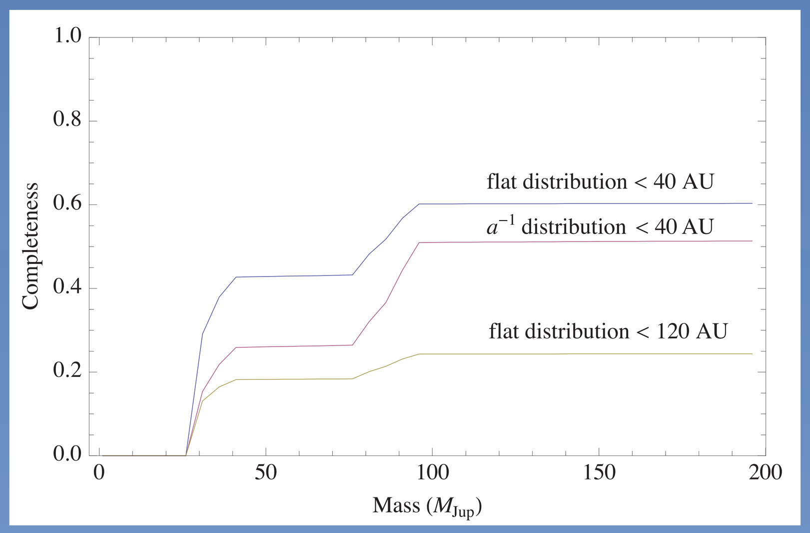
Population of detectable companions

We use a Monte Carlo simulation to generate a population of companions around each observed star.
Assuming a flat distribution of eccentricities between 0 and 0.8 and various distributions of semi-major axes, we draw companions at random positions on their orbits. The figure shows the projection on the sky for a sample population. The black circle corresponds to the field of view of the coronagraph.

For a given companion mass and estimated age, we use the models of Baraffe et al. (1998,2003) to calculate its brightness. For all our targets, self-luminosity of potential companions exceeds reflected light. Typically, we create a population of 10,000 companions, randomly positioned in their orbits, viewed at random inclinations, and identify those falling into the field-of-view of the coronagraph and bright enough to be detectable according to the dynamic range profile.

This figure shows the fraction of companion with a given mass that would have been detected around a G8 type star of 1.3 GYr at 11 pc. We considered three distributions: flat distributions up to 40 AU or 120 AU, and a hyperbolic distribution.

The figure shows that our sensitivity limit is about 25 Mjup for this star. This result is insensitive to the distribution of semi-major axes. At large masses the sensitivity is limited by the geometrical completeness (Brown 2005).



G8, 11pc, 1.3 GYr

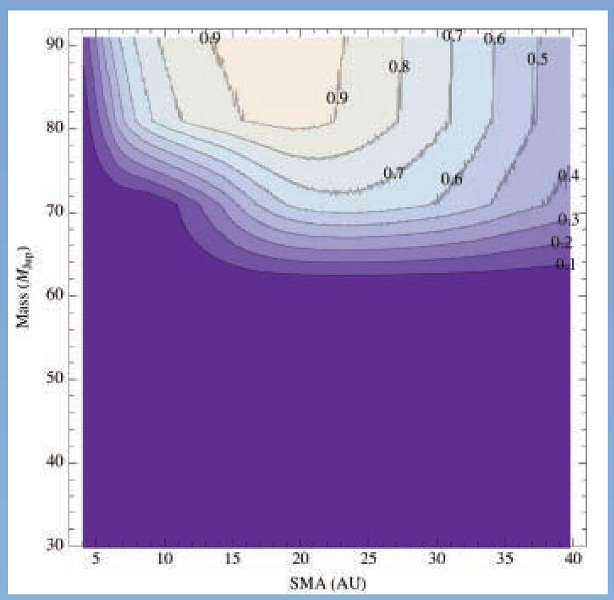
Completeness of observations

Each star is processed using the single or dual ADI method, depending on the rotation angles available for the observation, and a composite dynamic range is calculated. Using the age estimate of the star and theoretical models (Chabrier & Baraffe), we calculate the fraction of detectable companions (or completeness) for a given mass and semi-major axis, assuming a uniform distribution of eccentricities between 0 and 0.8.

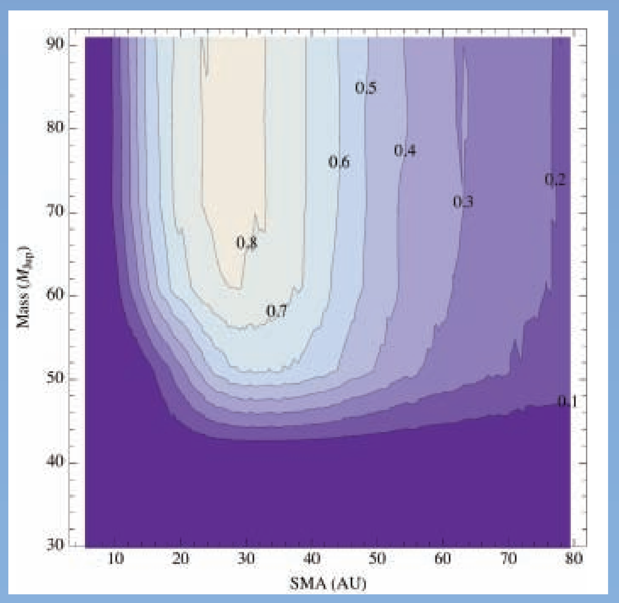
For example a contour region marked 0.7 means that 70% of the possible population of companion for this mass and semi-major axis would have been detected around this star.

The results vary from one star to another, depending on its age, distance, and magnitude. We give here three different cases, representative of the sample. For a given semi-major axis, the detectability depends on the mass of the companion which determines its brightness. At a given mass, the detectability depends on the geometry on the orbit and our field of view limitations.

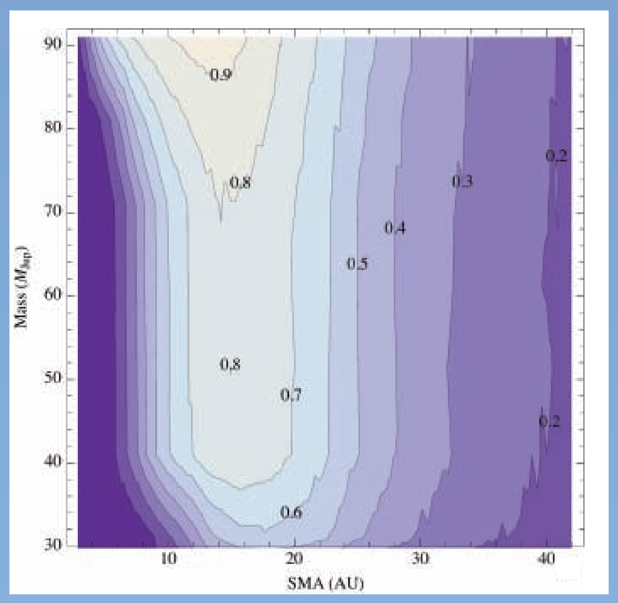
G6, 16pc, 11 GYr

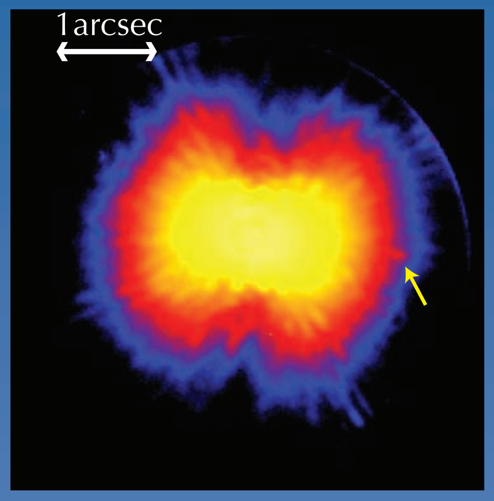


F6, 21pc, 1.5 GYr

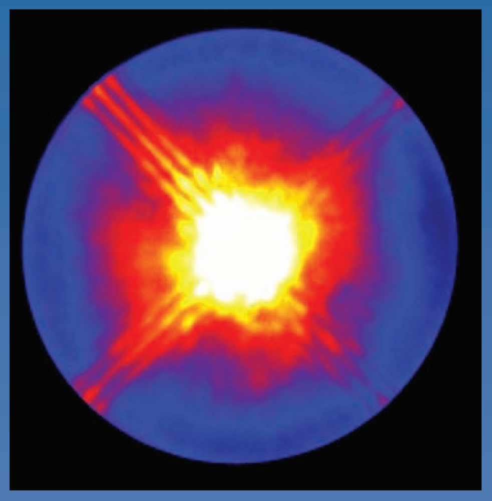


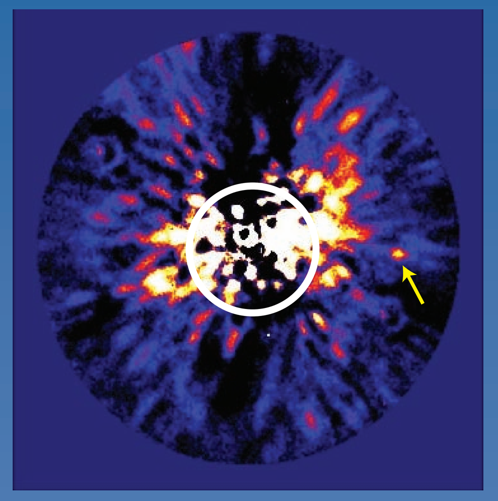
G8, 11pc, 1.3 GYr

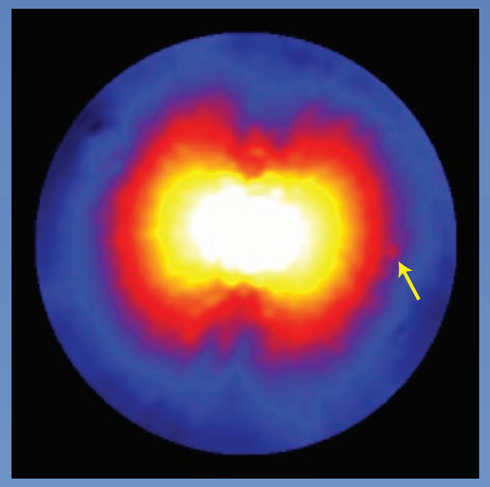


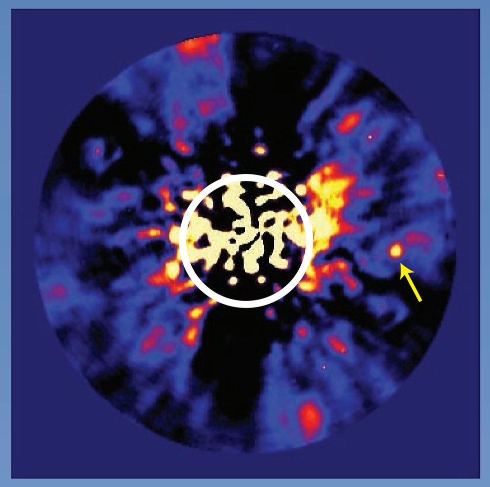


Short exposure before ADI
The spider diffraction is visible


Median image of the spiders
The object is not visible


Spider-subtracted image
The faint object is more visible


Long exposure before ADI
The faint object correspond to a 3-sigma level


Long exposure after ADI
The faint object correspond to a 9-sigma level

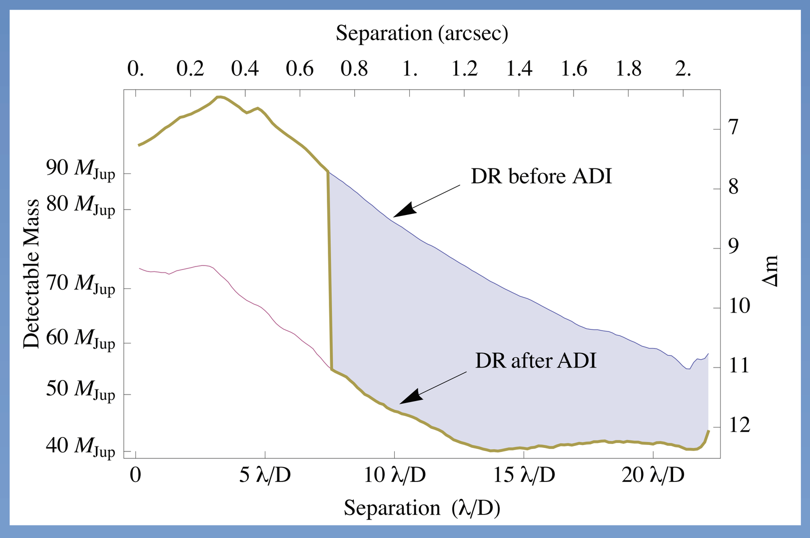
Data Processing and Dynamic Range

The coronagaph is at the Coudé Focus, and we can take advantage of the differential rotations between the detector, pupil and sky to remove the diffraction pattern of the spiders and that of the deformable mirror (DM) with its dead actuators (Sivaramakrishnan et al. 2006). We use the Angular Differential Imaging (ADI) method proposed by Marois et al. (2006).

The inner radius of validity of the ADI (white circle) is computed for both rotations so that a potential off-axis source is not subtracted out. In this example, only the pupil rotation gives a sufficient rotation, the second rotation is not considered. The ADI method also removes the average coronagraphic PSF profile.

The dynamic range (DR) is calculated from a local estimation of the variance of the noise in the processed image. Because of the radius limitation of the ADI method, we produce a composite DR plot. Typically the ADI method improves the DR by 1 to 2 magnitudes for the first region, and another 1/2 magnitude for the second, DM, rotation (when applicable).

Because the DR depends on the method used to estimate the variance of the noise, we created images with artificial companions at various signal to noise ratios for a chosen noise estimation method. Team members inspected the images by eye and converged at a detection level of 3.5 sigma. We use this rough estimate for the dynamic range estimation in the survey analysis. An example for a G8 type star of 1.3 GYr at 11 pc.is given below.

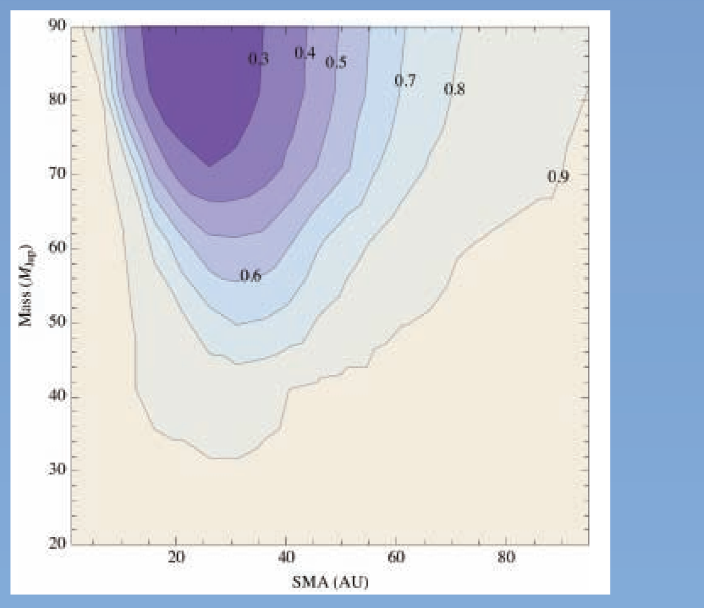


Companion frequency upper limits from non-detections

This figure combines the analysis for 15 stars observed in 2006 in which we did not detect companions. We calculate the maximum companion frequency in our sample by combining the individual completeness results using a Bayesian approach (Lafrenière et al. 2007).

The contours give the maximum companion frequency that is compatible with our observations as a function of mass and semi-major axis. For example, at semi-major axis 20AU, no more than 30% of stars have a companion of 80MJup. The strongest constraint on the frequency of companions is obtained where the detection is the easiest (i.e. the completeness is highest).

We will extend these preliminary results from the 2006 data to the entire survey.



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