A Coronagraphic Search for Sub-stellar Companions to Young Stars

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Abstract.

We are using NICMOS to search for very low-mass stellar and sub-stellar companions around nearby, young, main-sequence stars. With the coronagraph on Camera 2 and the F160W filter (1.4-1.8μm), we search in the region $0.4''$-$4''$ from the target star. We significantly increase our detection limit by subtracting observations made at two roll angles centered on the star and separated by 30 degrees. The lower mass limit of a detectable companion depends on the mass, age, and distance of the target star as well as the angular separation between star and companion. For several of our targets that are 10-50 Myr old, this lower mass limit could be as low as 10 Jupiter masses.

We present preliminary results using this technique. A stellar-like object with ΔH=5.3 was discovered $0.''9$ from HD 102982. From the distance and age of the primary, this companion is most likely a low-mass M star. Recent observations demonstrate that we can obtain a S/N = 5 (clear detection) on a secondary with ΔH=12 at a separation of 1".

1. Introduction

Searches for sub-stellar companions to main sequence stars and white dwarfs began over a decade ago utilizing both infrared (photometric) and optical (radial velocity) techniques. Brown dwarfs are objects thought to form like stars, but with insufficient mass ($\leq 0.08M_{\odot} = 80M_{Jupiter}$) to sustain hydrogen (H) burning within their interior. The best brown dwarf candidate for several years was the companion to the white dwarf GD 165 (Becklin& Zuckerman 1988, Zuckerman & Becklin 1992). Until recently it had the coolest temperature ($\approx$1800K) of any dwarf star, but it remained unclear if it was a very low-mass star or high-mass brown dwarf. Recent "all-sky" near-infrared surveys (2MASS & DENIS) may soon clarify whether 1800K objects are minimum-mass stars or brown dwarfs. The first undisputed brown dwarf was discovered as a companion to the M1V star GL 229 (Nakajima et al. 1995). The methane feature in the infrared spectrum of the companion clearly constrains its temperature below 1000K (Oppenheimer et al 1995), and models place its mass between 30 and 50 M_J (Burrows et al 1997).

The last two years have brought many discoveries. Presently, we now know of several suspected isolated brown dwarf objects in the Pleiades star cluster and solar neighborhood, and several planets around main-sequence stars. Yet, GD 165B and GL 229B remain the only sub-stellar *companions* to have been *directly* imaged. Low-mass objects are intrinsically faint and therefore hard to detect directly close to bright stars. With the resolution, current infrared capability, and high performance of the coronagraph of NICMOS on the Hubble Space Telescope, we can now attempt this daunting task.

1.1. Searching around young stars

Brown dwarfs and giant planets are more luminous when they are young, as they are still at a large radius, gravitationally contracting, and hot. Models of sub-stellar objects (Burrows et al 1997) show that $L \sim t^{-1.3}M^{2.24}$ based on cooling curves derived from atmospheric physics. If these models are correct, we can expect a brown dwarf/planet of $10M_J$ will be above $10^{-6}L_{\odot}$ when it is $\leq 10^8$ years old.

Numerous young stars within $\sim$ 50 pc of the sun have ages similar to the Pleiades ($\approx 10^8$yrs). This is deduced via inter-comparison of lithium abundance, Hα emission, Ca H & K line emission, kinematics, X-ray emission, and rotational velocity. Age estimates can be calibrated against samples of T Tauri stars and stars in young, nearby clusters such as the Pleiades and the Hyades and distances can be determined from parallax measurements. As part of our GTO program we have assembled a list of $\sim$50 stars thought to be young and nearby, with median age and distance of 0.1 Gyrs and 33pc, respectively.

The main problem with trying to image brown dwarfs or giant planets around main-sequence stars is the overwhelming brightness of the primary. A sub-stellar companion could be as much as 10^8 times fainter in bolometric luminosity than the star it orbits. A brown dwarf makes up some of this in the infrared, where it radiates most of its power, and is brighter with youth, but the primary can still be 10^4 times brighter. The orbit of a high mass planet is thought to be rather close to the star, as well, so high resolution, achievable from space, is needed. We will conduct our imaging survey with the coronagraph on Camera 2 at 1.6μm (F160W), which corresponds roughly to the H-band filter on the ground.

Not all sources in the field of view around the primary will necessarily be companions. Background objects could be unrelated stars or galaxies. With the excellent resolution on NICMOS, galaxies are easy to distinguish since they appear extended. As for point sources, the ultimate determinant of companionship is common proper motion. The target stars have been chosen for location away from the galactic plane: $\mid b \mid > 15°$. Therefore, we expect less than 0.02 background stars within $4''$ at H=22 for each star. Detections will be followed up to confirm companionship. For a candidate close-in ($< 4''$), for which the proper motion is enough ($> 0.''08$/yr), we will follow up with a later orbit on NICMOS. NICMOS has a limited lifetime and will be unusable after Dec 98. If the candidate is farther from the target star than $4''$, then ground-based follow-up will be possible to check proper motion. For close objects with smaller proper motions, or those we are unable to follow-up, we must wait for Adaptive Optics (AO) at Keck or Lick observations for confirmation. Keck might have a workable AO system by the first part of 1999 (Larkin, private comm).

Because the coronagraph is in a corner of the detector, this survey will only fully sample $0.''5$ to $4''$ around the primary star. At the average distance of 30 pc, this corresponds to 15-120 AU. This will sample the empirical maximum in the binary distribution of stars as well as the average distance of the giant planets in our own solar system (Duquennoy & Mayor 1991).

2. Observations with NICMOS

Our observational strategy places the target stars behind the coronagraph on Camera 2. The coronagraph is actually a hole in one of the mirrors of the optical path and combined with a Lyot stop, reduces the amount of light in the Airy rings of the point spread function rather than merely blocking light. With the target behind the coronagraph, we reduce the amount of light at the edge of the coronagraph by a factor of 4-6 (figure 1) compared to direct imaging. We have developed an observing strategy to go even deeper, as explained below.

The Hubble Space Telescope has the ability to slew in three directions: x, y, and θ. In order to keep the target star in the same position behind the coronagraph, as well as simplify the removal of the stellar profile, we designed two observations of the star at different spacecraft orientations ($\Delta\theta$) separated by 30 degrees. Therefore, the observing strategy is to place the young star behind the coronagraph, observe in the F160W filter (1.4-1.8μm) for about 700s, roll the telescope 30 degrees, and observe again for 700s. When we subtract the two images, the background from the star should subtract out (not quite completely due to some scattering) and if there are any additional objects in the field, two images (positive and negative) of each should remain (see figure 2). In the Orbital Verification testing (SMOV) of the camera, we found that this strategy worked as expected.

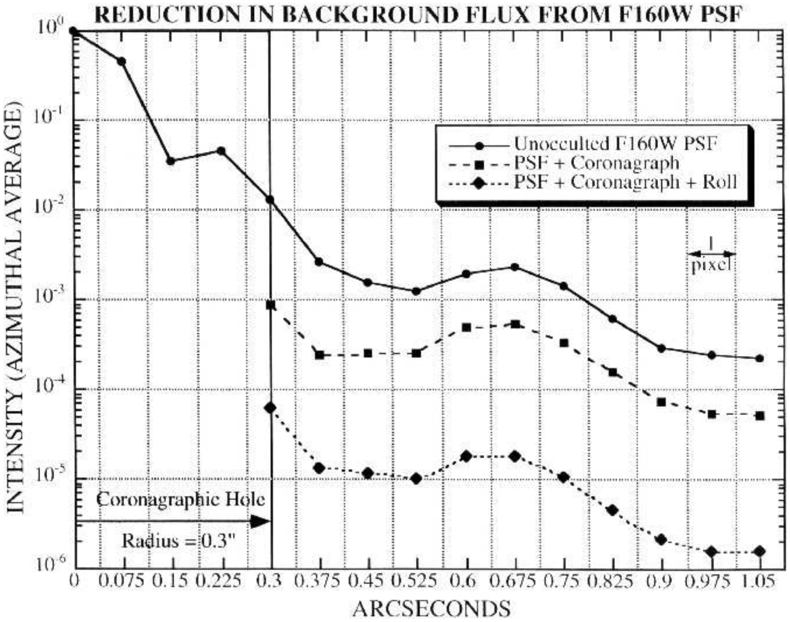

Fig.1: Measured background as an azimuthal average relative to the central pixel of a unocculted image in F160W (H-band) on the NICMOS camera. The background flux is reduced by placing the star behind the coronagraph (dashed line), and reduced even more from the roll subtraction of two images (dotted line). Results of SMOV test 7052 (Schneider & Lowrance, 1997)

According to models (Burrows et al 1997), a 0.1 Gyr old, 20 M_J brown dwarf will have an absolute H magnitude = 13.51 which corresponds to an apparent magnitude of 16.10 at the typical distance of our targets (d=30pc). In figure 1, early observations demonstrated that the background is 10^{-5} less than the star at $0.''5$. With a background $\approx$12 magnitudes fainter than our typical 6th magnitude target star, a 16.10 magnitude object should be easily detectable.

3. Preliminary Results

We present one of of first stars observed, HD 102982, a G3V star, m_H=6.9, 42 parsecs from the Sun. The NICMOS images revealed a stellar object $0.''9$ away which is fainter at H by 5.3 magnitudes. If it is a companion, then M_H=9.08 places it between M5 and M6 in photometric spectral class (Kirkpatrick & McCarthy 1994). The age of the star was thought to be close to the Pleiades age (0.1 Gyr) from X-ray luminosity (Lampton et al 1997) and Calcium H & K emission (Henry et al 1996). At this young age, the companion would be a candidate brown dwarf at the edge of 75 M_J. However, a recent finding (Soderblom et al 1998) shows the primary to be a spectroscopic binary with a period less than one month. This suggests that the activity once thought to be a signature of youth is more likely a product of a tidally-locked close binary system, and therefore the age of this system is unknown.

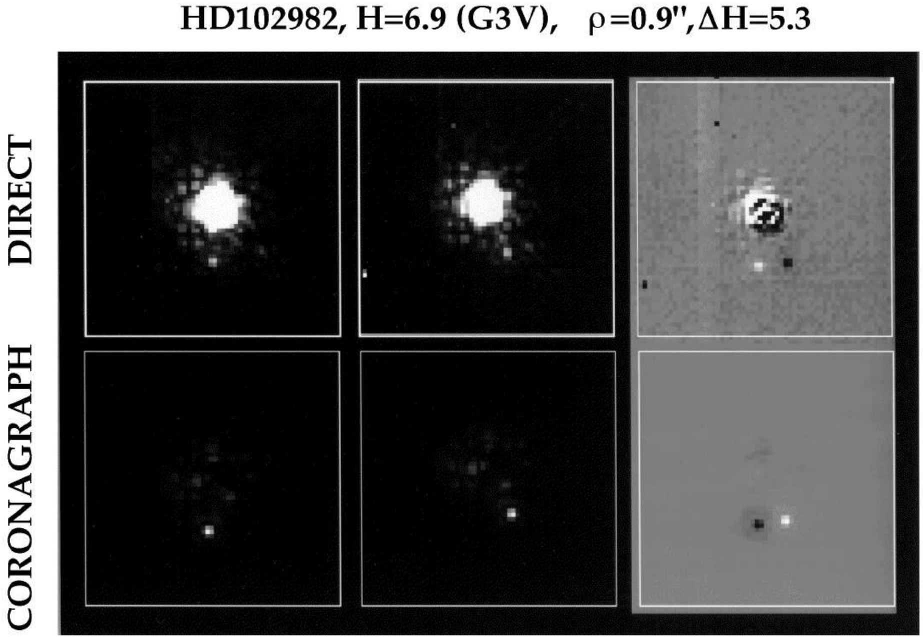

Fig.2: HD 102982 images with direct imaging (top panels) and with coronagraphic imaging (bottom panels). The direct images are from the acquisition with the F165M filter and are scaled to the F160W image. The far right panels are the subtraction of the two roll orientations; thus a positive and negative image exist.

4. Summary

To detect brown dwarfs or possible extra-solar giant planets, we are undertaking a coronagraphic imaging survey of young stars. We present observations of HD 102982 demonstrate our ability to detect sub-stellar objects. The possible companion, probably a low-mass M star, has a S/N$\approx$1600 (it is even visible in the 0.2s acquisition image) in the coronagraphic roll subtraction for a Δmag$\approx$5. From these observations, we should expect a Δmag$\approx$12 for a S/N=5 (a clear detection) at this separation of $1''$. Around this star, that would be a brown dwarf, and around some of our youngest stars, this brightness corresponds to $\leq$10M_J (age=15Myr). Clearly, we will be exploring down to the high-mass planet range with this survey.

References:

Becklin,E.E. & Zuckerman,B. 1988, Nature 336, 656
Burrows,A., Hubbard,W. Lunine,J., Marley,M., Huillot,T., Saumon,D., Friedman,R., 1997, ASP Conf. Series, 119, 9.
Duquennoy & Mayor 1991, A&A 248, 485
Henry,T.J., Soderblom,D.R., Donahue,R.A., & Balinus,S.L. 1996, AJ 111, 439
Kirkpatrick, J.D. & McCarthy,D.W.,Jr 1994, AJ 107, 333

Lampton.M., Lieu,R., Schmitt,J.H.M.M., Bowyer,S., Voges,W., Lewis,J. & Wu,X. 1997, ApJS 108, 545
Larkin, J. 1998 (private communication)
McCarthy,D.W.,Jr 1996 (private communication)
Nakajima,T., Oppenheimer,B.R., Kulkarni,S.R., Golimowski,D.A., Matthews,K. & Durrance,S.T. 1995, Nature 378, 464
Oppenheimer,B., Kulkarni,S., Matthews,K., Nakajima,T. 1995, Science 207, 1478.
Schneider,G. & Lowrance,P.J. SMOV/7052 Test Report
(http://nicmosis.as.arizona.edu/gschneid/7052_PS/)
Soderblom,D.R., King,J., Henry,T.J. 1998, AJ in press
Zuckerman,B. & Becklin,E.E. 1992, ApJ 386, 260