Mon. Not. R. Astron. Soc. **000**, 000–000 (0000) Printed 25 September 2002 (MN LATEX style file v2.2)

The spectroscopic signature of hot Jupiters in FU Orionis objects

Cathie J. Clarke[1⋆] and Philip J. Armitage[2,3]
[1]*Institute of Astronomy, Madingley Road, Cambridge CB3 0HA, UK*
[2]*JILA, University of Colorado, 440 UCB, Boulder CO 80309-0440, USA*
[3]*Department of Astrophysical and Planetary Sciences, University of Colorado, Boulder CO 80309-0391, USA*

25 September 2002

ABSTRACT
We show that if FU Orionis objects harbour hot Jupiters embedded in their discs, the resulting non-axisymmetric dissipation profile in the disc would be manifest as time-dependent distortions in the absorption line profiles of these objects. In order to affect the infrared line profiles, planets must lie within ~ 0.5 au of the central star, whereas only planets within ~ 0.1 au would influence the optical line profiles. The timescale for modulation of the line profiles is relatively short (months) in each case, so that the effect could not have been discovered from published spectra (which combine data taken in different observing seasons). The detection of hot Jupiters in FU Orionis objects would be in line with the expectations of tidal migration theories (which predict a high incidence of close planets around young stars) and would also lend support to models which link the triggering of rapid rise FU Orionis events to the existence of a close massive planet.

Key words: accretion, accretion discs — line: profiles — planets and satellites: formation — planetary systems: protoplanetary disks — stars: pre-main sequence — stars: individual (FU Orionis)

1 INTRODUCTION

Radial velocity surveys show that the frequency of massive planetary companions to late F and G dwarf stars on the main sequence is at least 6 percent. Around 1 percent of surveyed stars possess 'hot Jupiters', that is, massive planets within a tenth of an au of their parent star (Butler et al. 2000; Marcy & Butler 2000). Planetary migration theories (Lin & Papaloizou 1986; Lin, Bodenheimer & Richardson 1996) suggest that the abundance of such planets could be considerably higher in pre-main sequence stars, but even the main sequence numbers imply that a significant fraction – though probably not a majority – of pre-main sequence (T Tauri) stars harbour planetary companions at relatively small orbital radii. Directly detecting planets around T Tauri stars is, however, problematic. The rapid rotation of young stars means that searches for planetary transits have to contend with additional variability due to rotational modulation on a timescale of a few days (Aigrain, private communication), whilst the strong veiling of stellar absorption features in Classical T Tauri stars have made it difficult to detect even stellar companions by radial velocity methods (Mathieu 1994).

In this Letter, we point out that the subset of accreting pre-main sequence stars known as FU Orionis objects present a novel opportunity for searching for hot Jupiters. FU Orionis objects are believed to be episodes of enhanced accretion on to young stars, during which the emission from the central star is completely swamped by the accretion luminosity (corresponding to accretion rates of $\sim 10^{-5} - 10^{-4} M_{\odot} \mathrm{yr}^{-1}$; see Hartmann, Kenyon & Hartigan 1993; Kenyon 1995; Hartmann & Kenyon 1996 for reviews). During the outburst, both the broad band spectral energy distribution and the broad double peaked absorption lines of FU Orionis objects are well fit by the predictions of a steady state Keplerian accretion disc (Hartmann & Kenyon 1985, 1987; Kenyon, Hartmann & Hewett 1988; Popham et al. 1996). In Section 2, we show that the presence of a planet in the inner disc of an FU Orionis object would generate a non-axisymmetric pattern of disc emission, due to a high rate of accretion onto the planet from the disc. In consequence, the resulting line profiles are likely to be asymmetric and time variable, with the extra absorption moving between the red and blue wing of the line as the planet orbits. We present simple models of the predicted line profiles in this case. In Section 3 we discuss which lines provide the best diagnostics of hot Jupiters, and discuss the implications of a detection

⋆ email: cclarke@ast.cam.ac.uk

for planetary migration theory and the origin of FU Orionis outbursts.

2 NON-AXISYMMETRIC DISSIPATION AND SPECTRAL LINE PREDICTIONS

The interaction of a planet embedded within a viscous accretion disc has several facets. First, if the planet is sufficiently massive, gravitational torques from the planet will clear a gap (an annular region in which the surface density is greatly reduced as compared to the disc) in the disc (Goldreich & Tremaine 1980; Papaloizou & Lin 1984). Parameterizing the viscosity ν using the Shakura & Sunyaev (1973) α-prescription, $\nu = \alpha c_s^2/\Omega$, where c_s is the sound speed and Ω the angular velocity, gap opening occurs for a mass ratio $q = M_*/M_\mathrm{p}$ given by (Takeuchi, Miyama & Lin 1996),

$$q_\mathrm{crit} \gtrsim \left(\frac{h}{r}\right)^2 \alpha^{1/2}, \qquad (1)$$

where h/r is the relative scale height of the disc. Adopting parameters appropriate to discs during FU Orionis events (Bell & Lin 1994), we obtain,

$$q_\mathrm{crit} \gtrsim 4\times 10^{-3} \left(\frac{h/r}{0.2}\right)^2 \left(\frac{\alpha}{10^{-2}}\right)^{1/2}. \qquad (2)$$

This estimate suggests that because of the increased disc thickness during FU Orionis events, Jupiter mass planets will no longer be able to open a clean gap, and will instead be embedded within disc gas (Clarke & Syer 1996).

Second, irrespective of the presence or absence of a gap, there can be ongoing accretion from the disc onto the planet (Artymowicz & Lubow 1996). The planetary accretion rate can be expressed as a fraction of the disc accretion rate,

$$\dot{M}_\mathrm{p} = \epsilon(q)\dot{M}_\mathrm{disc}, \qquad (3)$$

where $\dot{M}_\mathrm{disc}$ is the accretion rate in the disc at a radius substantially greater than that of the planet. Simulations by Lubow, Seibert & Artymowicz (1999), D'Angelo, Henning & Kley (2002), and Bate et al. (2002) show that the efficiency factor $\epsilon \approx 1$ for a planet that is marginally able to open a gap. For larger masses, there is an approximately exponential suppression of the accretion efficiency (Lubow, Seibert & Artymowicz 1999). For lower mass planets ϵ also decreases, with a scaling variously measured as $M_p^{1/3}$ from 2D simulations (D'Angelo, Henning & Kley 2002) and as M_p in 3D calculations (Bate et al. 2002). In either event, Jupiter mass planets, embedded within the inner disc of FU Orionis objects, are expected to accrete mass at a significant fraction of the (very high) disc accretion rate.

Finally, the interaction of massive planets with the disc may induce eccentricity in both the disc material and the planetary orbit. Whether this occurs for Jupiter mass planets is currently uncertain (Papaloizou, Nelson & Masset 2001; Goldreich & Sari 2002; Ogilvie & Lubow 2002), and is probably dependent upon details of the angular momentum transport process in protoplanetary discs (e.g. Ogilvie 2001). We will ignore this possibility henceforth.

To verify some of these estimates, we have simulated the interaction between the planet and the disc using the ZEUS hydrodynamics code (Stone & Norman 1992). After 120 orbits of the embedded planet, by which time initial transients have died away, the surface density is as shown in Figure 1. As expected based on the arguments given above, the planet (here of mass 3 M_J, where M_J is the mass of Jupiter) is unable to clear a well-defined gap in a disc with parameters appropriate to FU Orionis systems, though there is a clear drop in the surface density at the radius where a gap would form in a cooler disc. A stream from the outer disc carries approximately half of the outer disc accretion rate, forming an (unresolved) circumplanetary disc and extending toward the inner boundary of the simulation.

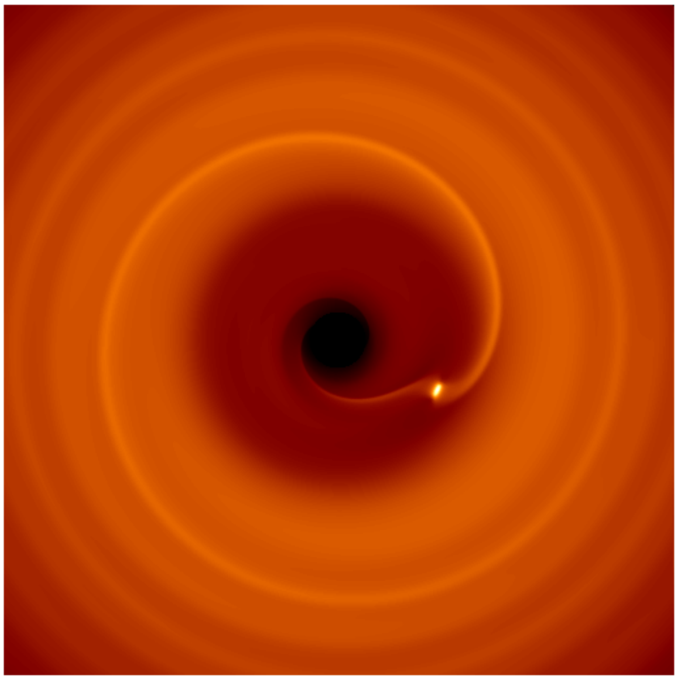

Figure 1. Surface density from an isothermal, two dimensional hydrodynamic simulation of the planet–disc interaction, with parameters appropriate for an FU Orionis event. We modeled a planet of mass 3 M_J, on a circular orbit in a disc with $c_s/v_\phi = 0.15$ at the orbital radius of the planet. Angular momentum transport was approximated using a constant kinematic viscosity corresponding to an α of 4×10^{-3} at the radius of the planet. The simulation was run using ZEUS at a numerical resolution of 240^2 grid points in cylindrical co-ordinates, with outflow boundary conditions at the radial edges of the grid.

Apart from gas in the (small) circumplanetary disc, the velocity perturbations to the disc flow are negligible. We have therefore modeled the influence of the planet upon the line profiles by assuming that the dominant effect is due to the enhanced dissipation caused by accretion onto the planet. The magnitude of the extra dissipation is,

$$\Delta L = \epsilon \frac{G M_p \dot{M}_\mathrm{disc}}{R_p} \qquad (4)$$

where R_p is the planetary radius. Since the disc is extremely optically thick, this extra luminosity will be radiated over a hotspot with a radius $\sim h \approx 0.2r$. The ratio of the effective temperature of the hotspot $\tilde{T}_e$ to the effective temperature T_e of the disc is then,

$$\frac{\tilde{T}_e^4}{T_e^4} \simeq 1 + \left(\frac{\epsilon}{0.25}\right)\left(\frac{M_p/M_*}{3\times10^{-3}}\right)\left(\frac{R_p}{5R_J}\right)^{-1}\left(\frac{r}{0.1\ \mathrm{au}}\right), \qquad (5)$$

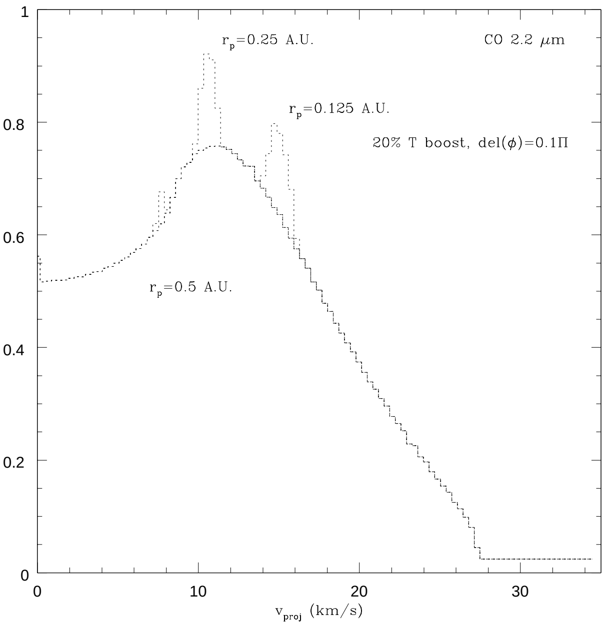

Figure 2. Model line profile for the spectral region centred on 2.2μm, the dashed lines corresponding to models in which a 'planet' is placed at the radii indicated. See text for further details.

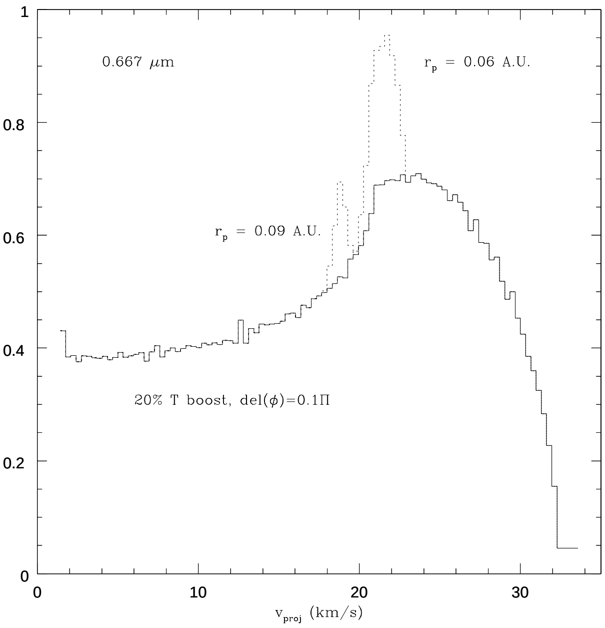

Figure 3. Model line profile for the spectral region centred on 6670 A, the dashed lines corresponding to models in which a 'planet' is placed at the radii indicated. See text for further details.

where R_J is the radius of Jupiter and we have chosen parameters appropriate to a system similar to that simulated in Figure 1. For these parameters, we estimate that the dissipation rate per unit area is about a factor of two greater in the vicinity of the planet than at other phases. In the case of optically thick emission, this corresponds to a 20 percent increase in the effective temperature of the disc in the region around the planet. As a result, extra absorption is produced at a velocity corresponding to the instantaneous line of sight velocity of the planet.

In Figures 2 and 3 we illustrate the resulting distortion of the line profile using a simplified model in which the absorption per unit area at each point in the disc is simply proportional to the black body emission flux at that point. (i.e. we neglect variations in the line equivalent width with either temperature or gravity over temperature ranges appropriate to the lines in question). A more sophisticated treatment would involve the summation of lines from appropriate stellar models, although it is unclear whether this is in fact more correct, given that in discs there is likely to be significant deposition of mechanical energy in the atmosphere, which makes comparison with stellar spectra problematical. In any case, Kenyon et al. (1988) noted that in the infrared, the saturated nature of the CO lines makes the equivalent widths rather insensitive to the effective temperature and gravity and a similar argument can be made for the principal lines in the 6170 A window (see discussion in Hartmann and Kenyon 1987).

The two spectral regions illustrated in Figures 2 and 3 correspond to bands centred on $2.2\mu m$ and $6170A$, and in each case we have followed Hartmann and Kenyon (1987) in assuming that the line equivalent width is zero outside the temperature ranges $900 - 5000$K (for the CO bands at 2.2μm) and $3300 - 6600$K (for the lines around $6170A$). For the temperature profile of the unperturbed disc, we have adopted the model of Kenyon et al. (1988) which provided the best fit to the spectral energy distribution and line profiles of V1057 Cygni: the disc temperature follows the classic $r^{-3/4}$ scaling with radius, with maximum temperature of $\sim$ 9000K at the disc's inner edge (0.016 au). Such a disc temperature distribution corresponds to an accretion rate of $\sim 10^{-4} M_{\odot}\mathrm{yr}^{-1}$ onto a solar mass star. Note that material at the inner edge of the disc is too hot to contribute to the absorption in either of the wavebands shown here and so there is likewise no contribution from any (presumably hotter) boundary layer.

In the absence of the planet, the absorption lines exhibit the double peaked structure familiar from the emission line profiles of cataclysmic variables. We have here scaled the velocities so as to roughly reproduce the line widths in V1057 Cyg, requiring the projected Keplerian velocity at the stellar surface to be $\sim$ 40 km s^{-1} (Kenyon et al. 1988). The maximum velocity corresponds to the projected velocity at the inner edge of the line producing region, whereas the velocity at the line peak reflects the projected velocity at the location where the line emissivity starts to fall (close to the Wien cutoff of the relevant transition). At lower velocities, the line is produced by a mixture of high velocity material projected at low velocity and by low velocity material absorbing in the Wien region of the spectrum. For the parameters employed here, the regions of the unperturbed disc that contribute to the line absorption lie between $0.025 - 0.07$ au (for the optical lines) and $0.04 - 0.4$ au (for the infrared lines).

We model the presence of the planet as a 20 percent boost in the effective temperature distributed in a region of azimuthal extent 0.1π and radial half-width $0.1 r_p$ centred

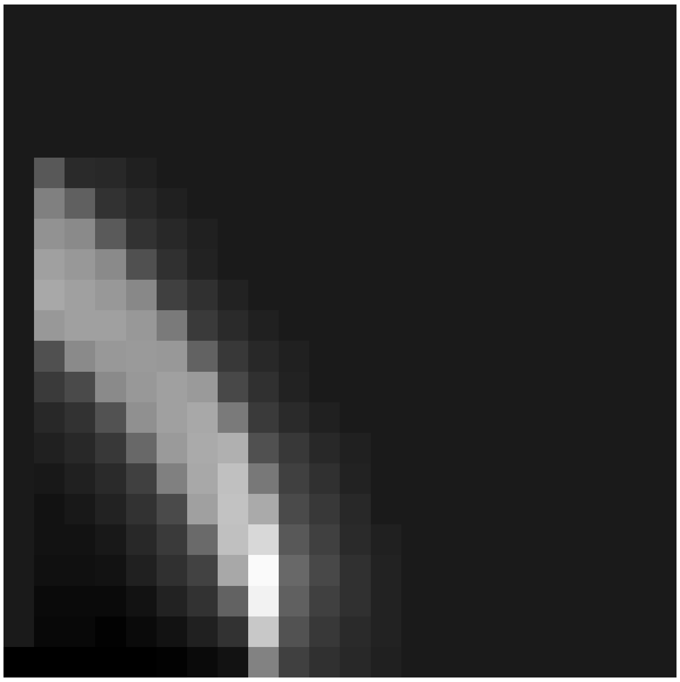

Figure 4. Trailed spectrum in the vicinity of the line centre (left margin of the plot) after subtraction of the mean line profile. The pixelation in λ reflects the achievable spectral resolution. The velocity shift during the orbit is likely to be more observable than the planet feature in any single spectrum.

on the planet at radius r_p, these choices being motivated by the preceding discussion. The effect of the planet is thus manifest in the absorption line profiles as additional absorption at the projected Keplerian velocity of the planet. It is evident from Figures 2 and 3 that the planet produces a distortion to the line profile whenever its associated region of enhanced dissipation overlaps the region of the disc producing the relevant line. The feature becomes less conspicuous, however, at lower velocities (i.e. within the peak of the line profile), since the contribution from the region disturbed by the planet is then diluted by the contribution from higher velocity material projected into this spectral region.

The features generated by the planet in Figures 2 and 3 are narrow, with velocity widths – comparable to the Keplerian shear across regions of the disc strongly perturbed by the planet – of only a few km/s. As such, they would be hard to resolve in individual spectra, even given the high spectral resolution of a new generation of infrared spectrometers such as NIRSPEC and Phoenix. On the other hand, line monitoring should reveal these features through their regular motion across the line profile. Figure 4 is a grey scale representation of the spectral variations produced at 2.2μm by a planet orbiting at 0.125 A.U., viewed at a spectral resolution of R=75,000. Each horizontal slice is a spectrum from which the mean line profile (over an orbit of the planet) has been subtracted. The planet's motion is along the line of sight at the bottom of the plot and the feature moves through the line centre (left hand margin) as the planet motion passes through the tangent plane. The characteristic trail produced by the planet is evident despite the inconspicuousness of the planet's feature in any individual spectrum.

3 THE DETECTABILITY OF HOT JUPITERS IN FU ORIONIS SYSTEMS

The above crude model suggests that the sort of non-axisymmetric dissipation profile that one would associate with an embedded hot Jupiter would have a conspicuous effect on the line profiles of FU Orionis systems. This immediately raises the question of whether such a distortion should already have been detected in FU Orionis objects analysed to date if they indeed harboured such planets. Two factors however militate against the discovery of such features in existing spectra: firstly the limited spectral resolution (particularly in the infrared, where the spectral resolution of published spectra is comparable with the line width) and secondly, the fact that in order to enhance the signal to noise of the lines analysed, spectra have been co-added from a number of observing runs. We have seen above that the regions of the disc in which embedded planets would be detectable in this way are close in (within 0.5 au) and hence the associated orbital timescale is short (months). The effect of a feature crossing the line profile from the red to the blue wing would thus be washed out by combining spectra from different observing seasons.

In order to detect an embedded planet through its time-dependent distortion of the line profile, it is of course necessary that the planet be located in the region of the disc producing the line. This restricts the technique to the detection of rather close planets (within ~ 0.5 au for an effect to be manifest in the infrared lines and within ~ 0.1 au for a manifestation in optical line spectra). Such orbital radii are well within the range of separations of hot Jupiters (to date 37 and 18 exoplanets respectively have been discovered in each of these separation ranges[1]). Since the infrared lines are produced in cooler regions of the disc, it follows that the infrared lines provide a good diagnostic of planets over a larger range of radii. On the other hand, since the optical lines originate in a more spatially restricted region of the disc, it is evident that *if* a planet is present at an appropriate radius, it will be more conspicuous in the optical line profiles, since the distortion produced by the planet is less diluted by absorption by other annuli.

What, then, is the likelihood of there being an appropriate planet in a FU Orionis system? If the incidence of planets in FU Orionis systems follows the statistics of exoplanets around main sequence stars, then we expect that between 2 and 3 percent of systems will harbour a planet within 0.5 au. There would then be little chance of there being an exoplanet in the ≈ 16 systems classified as FU Orionis systems to date (Sandell & Weintraub 2001). There are, however, strong theoretical arguments that close planets should have been commoner during the pre-main sequence stage, and that the incidence of such systems on the main sequence represents only the (possibly small) fraction that survived migration without being swallowed by the star (Lin, Bodenheimer & Richardson 1996; Trilling et al. 1998; Armitage et al. 2002; Trilling, Lunine & Benz 2002). Indeed, given the extreme youth of most FU Orionis systems, it is probable that *all* close planets present in FU Orionis discs

[1] See e.g. the compilation at `exoplanets.org`, though note that many of the planets within 0.1 au have $M_p \sin(i)$ less than a Jupiter mass.

are destined to be swallowed, in which case main sequence statistics provide no constraint whatsoever on the possible population. Although it is impossible to assess by what factor the incidence of hot Jupiters is increased in young stars, the sign of the effect should motivate the search advocated here.

Finally, we remark that FU Orionis objects may be prime targets for detecting hot Jupiters if, as suggested by Clarke and Syer (1996), there is a causal link between the two phenomena. Clarke and Syer (1996) argued that the most plausible way of triggering a rapid rise outburst (i.e. one in which the hundredfold increase in luminosity occurs on a timescale of a few months), is if the disc prior to outburst is 'dammed up' behind such a planet. In the Clarke and Syer model, the onset of the thermal ionisation instability upstream of the planet causes the dam to burst, enveloping the planet and causing a rapid rise in accretion luminosity. It is notable that the planetary characteristics advocated by Clarke and Syer (a 10 Jupiter mass planet located at ~ 0.1 au), are just such that they would be detectable through the absorption line diagnostics discussed here. V1057 Cygni and FU Orionis (both of which are of the rapid rise variety and which are well studied spectroscopically) are thus both prime candidates for this sort of investigation.

ACKNOWLEDGEMENTS

We thank Doug Lin for useful discussions on the possibility of pre-main-sequence hot Jupiters, and Mark McCaughrean and Keith Horne for advice concerning the observability of the effect. PJA gratefully acknowledges support from the IOA Visitors Grant.

REFERENCES

Armitage P.J., Livio M., Lubow S.H., Pringle J.E., 2002, MNRAS, 334, 248
Artymowicz P., Lubow S.H., 1996, ApJ, 467, L77
Bate M.R., Lubow S.H., Ogilvie G.I., Miller K.A., 2002, MNRAS, submitted
Bell K.R., Lin D.N.C., 1994, ApJ, 427, 987
Butler R.P., Marcy G.W., Vogt S.S., Fischer D.A., 2000, in Planetary Systems in the Universe, eds A.J. Penny, P. Artymowicz, A.-M. Lagrange, and S.S. Russell, IAU Symposium 202, p. 1
Clarke C.J., Syer D., 1996, MNRAS, 278, L23
D'Angelo G., Henning T., Kley W., 2002, A&A, 385, 647
Goldreich P., Sari R., 2002, ApJ, submitted (astro-ph/0202462)
Goldreich P., Tremaine S., 1980, ApJ, 241, 425
Hartmann L., Kenyon S.J., 1985, ApJ, 299, 462
Hartmann L., Kenyon S.J., 1987, ApJ, 312, 243
Hartmann L., Kenyon S.J., 1996, ARA&A, 34, 207
Hartmann L., Kenyon S., Hartigan P., 1993, in Protostars and Planets III, eds E. Levy and J.I. Lunine, University of Arizona Press, p. 497
Hartmann L., Kenyon S.J., Hewett R., 1988, ApJ, 325, 231
Kenyon S.J., 1995, Rev. Mex. Astron. Astrophy. Conf. Series, 1, 237
Lin D.N.C., Bodenheimer P., Richardson D.C., 1996, Nature, 380, 606
Lin D.N.C., Papaloizou J.C.B., 1986, ApJ, 309, 846
Lubow S.H., Seibert M., Artymowicz P., 1999, ApJ, 526, 1001
Marcy G.W., Butler R.P., 2000, PASP, 112, 137
Mathieu R.D., 1994, ARA&A, 32, 465
Ogilvie G.I., 2001, MNRAS, 325, 231
Ogilvie G.I., Lubow S.H., 2002, ApJ, submitted (astro-ph/0208363)
Papaloizou J.C.B., Lin D.N.C., 1984, ApJ, 285, 818
Papaloizou J.C.B., Nelson R.P., Masset F., 2001, A&A, 366, 263
Popham R., Kenyon S., Hartmann L., Narayan R., 1996, ApJ, 473, 422
Sandell G., Weintraub D.A., 2001, ApJS, 134, 115
Shakura N.I., Sunyaev R.A., 1973, A&A, 24, 337
Stone J.M., Norman M.L., 1992, ApJS, 80, 753
Takeuchi T., Miyama S.M., Lin D.N.C., 1996, ApJ, 460, 832
Trilling D.E., Benz W., Guillot T., Lunine J.I., Hubbard W.B., Burrows A., 1998, ApJ, 500, 428
Trilling D.E., Lunine J.I., Benz W., 2002, A&A, in press