Final Report on Proposal NAGW-4156: "Planet Forming Protostellar Disks" 1994-1998

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1 Introduction

The proposal achieved many of its objectives. The main area of investigation was the interaction of young binary stars with surrounding protostellar disks. A secondary objective was the interaction of young planets with their central stars and surrounding disks. The grant funds were used to support visits by coIs and visitors: Pawel Artymowicz, James Pringle, and Gordon Ogilvie. Funds were also used to support travel to meetings by Lubow and to provide partial salary support.

2 Binary-Disk Interactions

2.1 Disk Sizes

We investigated the gravitational interaction of a generally eccentric binary star system with circumstellar and circumbinary protostellar disks. We determined the disk sizes for tidally truncated disks using SPH simulations and analytic methods (Artymowicz and Lubow 1994, 1995). These results have been used to infer properties of young binaries with observed disks, such as GG Tau (Dutrey et al 1994) and HK Tau (Stapelfeldt et al 1998).

2.2 Orbital Evolution

We determined the effects of circumbinary and circumstellar disks on the binary orbital evolution. Analytical and numerical approaches were used to determine the semimajor axis evolution and eccentricity evolution of a binary due to disk interactions (Lubow and Artymowicz 1996, 1998). These studies provide a basis for understanding the eccentricity distribution of young binary stars (Mathieu 1994) and possibly for the eccentricity distribution of planets (Mazeh et al 1997).

2.3 Mass Flows Through Gaps

Tidal forces create gaps that separate circumstellar and circumbinary disks. We found through simulations that for somewhat warm and turbulent disks, mass flows can occur through gaps (Artymowicz and Lubow 1996). Material can flow from the inner edge of the circumbinary disk through the gap and become accreted by the central binary. In the way, the circumstellar disks would not be depleted. Some evidence for these flows has been found in studies of infrared companions or IRCs (Koresko et al 1997) and in young binary DQ Tau (Mathieu et al 1997).

3 Waves in Protostellar Disks

The torques that binaries or planets exert on disks are dominated by resonant effects (e.g., Goldreich and Tremaine 1979, Ward 1986, Savonije et al 1994). At resonances, waves are launched that carry energy and angular momentum. For a disk that is vertically isothermal, the work cited above can be directly applied. A disk may not always be vertically isothermal, in particular if it is optically thick and has internal dissipation. Previous numerical approaches to this problem ascribed the behavior to refraction (Lin et al 1990). We investigated the behavior of the waves semianalytically (Lubow and Ogilvie 1998, Ogilvie and Lubow 1999). We found that the waves are channeled to the disk surface as they achieve wavelengths that are less than the disk thickness. They behave as incompressible gravity waves. Nonlinear wave damping is expected under some conditions.

4 Star-Planet Interactions

The discovery of extra-solar planets around solar-type stars (Marcy and Butler 1998, Mayor et al 1998) raised several questions about their interactions with the central star.

4.1 Effects Due to Star

The close-orbiting planets such as 51-Peg are subject to potentially strong tidal forces due to the central star. We investigated the orbital evolution of a such a planet and found that it is tidally unstable to orbital decay (Rasio et al 1995). However, because of the weakness of the tidal dissipation by the star even at such close distances, the decay timescale is longer than 10^{10} years.

4.2 Effects Due to the Planet

The outer layers of a close-orbiting gas gaint planet are isothermal, due to the strong heating by the central star (Guillot et al 1996). A tidal resonance can occur within the planet at the interface between the convectively stable outer isothermal layers and the convective unstable interior (Lubow et al 1997). As a result of this tidal resonance, the state of the planet can be affected. The timescale for spin synchronization was crudely estimated to be very short compared with its lifetime. The orbital eccentricity decay is considerably longer, but may be of significance.

5 Publications Resulting from Grant

Artymowicz, P. and Lubow, S.H. 1994, "Dynamics of Binary-Disk Interactions: Resonances and Disk Gap Sizes", ApJ, 421, 651.

Artymowicz, P. and Lubow, S.H. 1995, "Interactions of Young Binaries with Protostellar Disks", in Disks and Outflows around Young Stars, eds. Staude, H.J., Beckwith S., et al (Springer Verlag)

Artymowicz, P. and Lubow, S.H. 1996, "Mass Flow Through Gaps in Circumbinary Disks", ApJL, 476, L77.

Artymowicz, P., Lubow, S.H., and Kley 1998, "Planetary Systems and Their Changing Theories", "Planetary Systems - the long view", Eds. L. Celnikier et al., Editions Frontieres, in press.

Lubow, S.H. and Artymowicz, P. 1996, "Young Binary Star/Disk Interactions", NATO ASI 477, eds. R. Wijers, M. Davies, C. Tout, Kluwer, p. 53.

Lubow, S.H. and Artymowicz, P. 1997, "Young Binary Star/Disk Interactions", in IAU Colloquium 163.

Lubow, S.H. and Artymowicz, P. 1998, "Interactions of Young Binaries with Disks", Protostars and Planets IV, eds. Mannings, V., Boss. A., Russell, S., Space Science Series (University of Arizona Press), in press

Lubow, S.H. and Ogilvie, G.I. 1998, "Three-Dimensional Waves Generated at Lindblad Resonances in Thermally Stratified Disks", ApJ, 504, 983

Lubow, S.H. and Ogilvie, G.I. 1999, "The Effect of an Isothermal Atmosphere on the Propagation of Three-Dimensional Waves in a Thermally Stratified Accretion Disk", ApJ, in press

Lubow, S.H., Tout, C.A., and Livio, M. 1997, "Resonant Tides in Close Orbiting Planets", ApJ, 484, 866.

Rasio, F.A., Tout, C.A., Lubow, S.H., and Livio, M. 1996, "Tidal Decay of Close Planetary Orbits", ApJ, 407, 1187.

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Goldreich, P., and Tremaine, S. 1979, ApJ, 233, 857

Guillot, T., Burrows, A., Hubbard, W.B., Lunine, J.I., and Saumon, D. 1996, ApJ, 459, L35

Koresko, C.D., Herbst, T.M., and Leinert, Ch. 1997, ApJ, 480, 741

Lin, D.N.C., Papaloizou, J.C.B., and Savonije, G.J. 1990, ApJ, 364, 326

Marcy, G.W. and Butler, R.P. 1998, ARAA, 36, 57

Mayor, M., Udry, S., and Queloz, D. 1998, ASP Conf. Ser. 154, The Tenth Cambridge Workshop on Cool Stars, Stellar Systems and the Sun, Edited by R. A. Donahue and J. A. Bookbinder, p.77

Mathieu, R.D. 1994, ARAA, 32, 465

Mathieu, R.D., Stassen, K., Basri, G., Jensen, E.L.N., Johns-Krull, C.M., Valenti, J.A., and Hartmann, L.W. 1997, AJ, 113, 1841

Mazeh, T., Mayor, M., and Latham, D. 1997, ApJ, 478, 367

Savonije, G.J., Papaloizou, J.C.B., and Lin, D.N.C. 1994, MNRAS, 268, 13

Stapelfeldt, K.R., Krist, J.E., Menard, F., Bouvier, J., Padgett, D.L., Burrows, C.J. 1988, ApJ, 502, 65

Ward, W.I. 1986, Icarus, 67, 164

Final Patent/Invention Report

Grant #: NAGW-4156
Title: Properties of Planet Forming Protostellar Disks
Principal Investigator: Dr. Steve Lubow

No patents or inventions resulted from this grant.

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6. Letter of credit number: 100040

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Give total number for this period

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I certify to the best of my knowledge and belief that this report is true in all respects and that all disbursements have been made for the purpose and conditions of the grant or agreement

AUTHORIZED CERTIFYING OFFICIAL

SIGNATURE: Marianne W Johnson

DATE REPORT SUBMITTED: 5/2/99

TYPED OR PRINTED NAME ~~AND~~ TITLE: MARIANNE W. JOHNSON, Senior Accountant

TELEPHONE: (410) 338-4812

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