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 cols 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 giant 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


OTHER REFERENCES


Marcy, G.W. and Butler, R.P. 1998, ARAA, 36, 57
Mathieu, R.D. 1994, ARAA, 32, 465
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.
FEDERAL CASH TRANSACTION REPORT

(See instructions on the back. If report is for more than one grant or assistance agreement, attach completed Standard Form 272-A.)

2. RECIPIENT ORGANIZATION
Name
SPACE TELESCOPE SCIENCE INSTITUTE
Number and Street
3700 SAN MARTIN DRIVE
City, State & Zip Code:
BALTIMORE, MD 21218

3. FEDERAL EMPLOYER IDENTIFICATION NO.
86-0138043

4. FEDERAL GRANT OR OTHER IDENTIFICATION NUMBER
NAGW-4156

5. RECIPIENT'S ACCOUNT NUMBER
K0982

6. LETTER OF CREDIT NUMBER
100040

7. LAST PAYMENT VOUCHER NUMBER
N/A

8. PAYMENT VOUCHERS CREDITED TO YOUR TREASURY CHECKS RECEIVED
Account: $74,960.08 $0.00

9. PERIOD COVERED BY THIS REPORT
FROM: 10/01/97 TO: 09/30/98

11. STATUS OF FEDERAL CASH
a. Cash on hand beginning of reporting period. 0.00
b. Letter of credit withdrawals - wire transfer 74,960.08
c. Treasury check payments 0.00
d. Total receipts (sum of lines b and c) 74,960.08
e. Total cash available (Sum of lines a and d) 74,960.08
f. Gross disbursements 74,960.08
(g. Federal share of program income 0.00
h. Net disbursements (Line f minus line g) 74,960.08
i. Adjustments of prior periods 0.00
j. Cash on hand end of period 0.00

12. THE AMOUNT SHOWN ON LINE 11J, ABOVE, REPRESENTS CASH REQUIREMENTS FOR THE ENSUING DAYS

13. OTHER INFORMATION

14. REMARKS (Attach additional sheets of plain paper, if more space is required)

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NAGW-4156

15. 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.

Certification
AUTHORIZED CERTIFYING OFFICIAL

SIGNATURE
MARIANNE W. JOHNSON, Senior Accountant

DATE REPORT SUBMITTED
5/2/98

PREVIOUS FORM 272-101
STANDARD FORM 272 (7-76)
Prescribed by Office of Management and Budget
**FEDERAL CASH TRANSACTION REPORT CONTINUATION**

(This form is completed and attached to Standard Form 272 only when reporting more than one grant or assistance agreement.)

2. **RECIPIENT ORGANIZATION** (Give name only as shown in item 2, SF 272)

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3. **PERIOD COVERED BY THIS REPORT** (As shown on SF 272)

   FROM (month, day, year) 10/01/97 TO (month, day, year) 09/30/98

4. **List information below for each grant or other agreement covered by this report. Use additional forms if more space is required.**

   **FEDERAL GRANT OR OTHER IDENTIFICATION NUMBER**
   (Show a subdivision by other identifying numbers if required by the Federal Sponsoring Agency)

   **RECIPIENT ACCOUNT NUMBER OR OTHER IDENTIFYING NUMBER**

   (a) NAGW-4156 (b) K0982

   **FEDERAL SHARE OF NET DISBURSEMENTS**

   **CUMULATIVE NET DISBURSEMENTS (Gross disbursements less program income received) FOR REPORTING PERIOD**

   (c) 0.00 (d) 74,960.08

5. **TOTALS** (Should correspond with amounts shown on SF 272 as follows: column (c) the same as line 11b; column (d) the sum of lines 11b and 11i of this SF 272 and cumulative disbursements shown on last report. Attach explanation of any differences.)

   $0.00 $74,960.08