PROTOSTARS AND DISKS

GRANT NAGW-3121

Final Report

For the Period 1 September 1992 through 31 August 1996

Principal Investigator

Dr. Paul Ho

May 1997

Prepared for
National Aeronautics and Space Administration
Washington, D.C.

Smithsonian Institution
Astrophysical Observatory
Cambridge, Massachusetts 02138

The Smithsonian Astrophysical Observatory is a member of the Harvard-Smithsonian Center for Astrophysics

Final Report
NASA Grant NAGW-3121
P.I.: Paul T.P. Ho
Title: Protostars and Disks
Grant Period: September 1, 1992 to August 31, 1996

During the support period, we have made great progress on our studies of protostars and disks. Attached is a list of our publications and submitted papers while supported by our grant. Our goal was to concentrate on high angular resolution (arc-second scale) studies of molecular cloud cores associated with very young star formation. We also explored new ways to study disks and protoplanetary systems. We summarize and describe our findings here in this report.

Molecular Cloud Studies. Using a number of interferometers, including the VLA, BIMA, OVRO, and NMA, we continue our program to study the molecular cloud cores in a number of star forming regions. These include studies of Cepheus A (Publ. 2, 7), NGC2024 (Publ. 5), GM24 (Publ. 6), CTB80 (Publ. 10), Herbig-Haro 1 (Publ. 11, 15), Herbig-Haro 34 (Publ. 17), G5.48-0.24 (Publ. 23), Orion (Publ. 32), Herbig-Haro 25-26 (Publ. 35), GSS 30 (Publ. 38), and L723 (Publ 40). What we have found in these studies are the readily detectable signatures of the underlying physical processes. For example, localized heating and enhanced linewidths are good indicators of an embedded exciting source. Interactions between outflows and the local environment suggest that outflow morphology can be strongly influenced by interactions.

Gravitational Contraction. We have also continued to study the kinematical signatures of contractions. Specific cases which we examined include G10.6-0.4 (Publ. 13), Herbrig-Haro 1 (Publ. 15), G45.47+0.05 (Publ. 27), L1551-IRS5 (Publ. 31), W51 (Publ. 34, 41, 43), IRAS04368+2557 (Publ. 37), IRAS04169+2702 and IRAS04365+2535 (Publ. 39). In the cases where a strong continuum emission source is available, contraction can be identified by the red-shifted absorption seen projected against the continuum source. In the low mass cases, where continuum emission is not available, rotation and contraction can be distinguished by resolving the velocity field and modeling.

Jets, Winds, and Outflows. It is now well known that outflows and winds are extremely prevalent in the early stages of star formation. We have also studied the relation of outflows to the presence of disk-like structures. The souces which were studied include HL Tau (Publ. 14), W51 (Publ. 20), L1157 (Publ. 21), Serpens FIRS 1 (Publ. 24), W33A (Publ. 28), and W75N (Publ. 42). We find that the large scale outflows are often driven by an underlying radio jet which is collimated at the AU scale. A circumstellar disk is probably associated with the radio jet and can be traced sometimes by the presence of H_2O masers. The large scale outflows can be traced in increasing number of molecules which has allowed the study of shock chemistry.

Circumstellar Disks. The goal of studying molecular cloud cores, especially in the context of the NASA Origins Program, is to try to discover the disks which may be the precursors of protoplanetary systems. Here, we pursued a few systems which reveal structures at the 100 AU scale. These are Cepheus A (Publ. 7), 26), HL Tau (Publ. 9, 14, 33), L1551-IRS5 (Publ. 9, 31), and W75N (Publ. 42). Dust continuum emission, molecular line emission and H_2O masers may be the best tracers of such compact disks.

Extrasolar Planetary Systems. To push to even smaller scales, we have been investigating direct detection of planets. Our first efforts are toward detecting brown dwarfs. Here we are employing differential methane band imaging at 2 microns in order to detect brown dwarf candidates. Only brown dwarfs have atmospheres that are cool enough to sustain methane while at the same time have enough luminosity to serve as a background. Hence methane band absorption can be seen toward a brown dwarf but not against the primary star. Differential imaging was successful in detecting GL229B (Publ. 36), and we are continuing to search for other candidates.

Support of Students. This grant also supported in part graduate students Jennifer Wiseman (Ph.D. Harvard 1995), Qizhou Zhang (Ph.D. Harvard 1997), Jose Girart (Ph.D. Barcelona 1997), and also postdoctoral fellow Hua Chen (1996).

Publications 1992-1997

Paul T. P. Ho

1. "Warm Molecular Gas in a Starburst: CO (3–2) Observations of Maffei 2," Hurt, R.L., Turner, J.L., Ho, P.T.P., and Martin, R.N., *Ap. J.*, **404**, 602 (1993).
2. "A Circumstellar Molecular Gas Structure Associated with the Massive Young Star Cepheus A-HW 2," Torrelles, J.M., Rodríguez, L.F., Cantó, J., and Ho, P.T.P., *Ap. J. (Letters)*, **404**, L75 (1993).
3. "The Centre of the Milky Way," Blitz, L., Binney, J., Lo, K.Y., Bally, J., and Ho, P.T.P., *Nature*, **361**, 417 (1993).
4. "Heterogenous Array Observations of IC 342: The CO Isotopic Ratio," Wright, M.C.H., Ishizuki, S., Turner, J.L., Ho, P.T.P., and Lo, K.Y., *Ap. J.*, **406**, 470 (1993).
5. "A Flattened Cloud Core in NGC2024," Ho, P.T.P., Peng, Y.L., Torrelles, J.M., Gómez, J.F., Rodríguez, L.F., and Cantó, J., *Ap. J.*, **408**, 565 (1993).
6. "Further Studies on the Champagne Phase of GM 24 (IRAS 17136-3617)," Gómez, J.F., Torrelles, J.M., Tapia, M., Gómez, Y., Rodríguez, L.F., Roth, M., and Ho, P.T.P., *Ap. J.*, **409**, 269 (1993).
7. "From Bipolar to Quadrupolar: The Collimation Processes of the Cepheus A Outflow," Torrelles, J.M., Verdes-Montenegro, L., Ho, P.T.P., Rodríguez, L.F., and Cantó, J., *Ap. J.*, **410**, 202 (1993).
8. "HI Streamers Around M82: Tidally Disrupted Outer Gas Disk," Yun, M.S., Ho, P.T.P., and Lo, K.Y., *Ap. J. (Letters)*, **411**, L17 (1993).
9. "Upper Limits to the Detection of Ammonia from Protoplanetary Disks Around HL Tau and L1551-IRS 5," Gómez, J.F., Torrelles, J.M., Ho, P.T.P., Rodríguez, L.F., and Cantó, J. *Ap. J.*, **414**, 333 (1993).
10. "Interaction Between the Supernova Remnant CTB 80 and the Ambient Interstellar Medium: HI and CO Observations," Koo, B.-C., Yun, M.S., Ho, P.T.P., and Lee, Y. *Ap. J.*, **417**, 196 (1993).
11. "Ammonia Emission Downstream of the Herbig-Haro Object 1," Torrelles, J.M., Gómez, J.F., Ho, P.T.P., Anglada, G., Rodríguez, L.F., and Cantó, J. *Ap. J.*, **417**, 655 (1993).
12. "Bright Radio Continuum Emission from Star Formation in the Cores of Nearby Spiral Galaxies," Turner, J.L., and Ho, P.T.P. *Ap. J.*, **421**, 122 (1994).
13. "The Rotating Molecular Core in G10.6-0.4: Synthesis Maps in $^{12}C^{18}O$," Ho, P.T.P., Terebey, S., and Turner, J.L. *Ap. J.*, **423**, 320 (1994).

14. "Subarcsecond VLA Images of Disk and Jet in HL Tau," Rodríguez, L.F., Cantó, J., Torrelles, J.M., Gómez, J.F., Anglada, G., and Ho, P.T.P. *Ap. J.*, **427**, L103 (1994).

15. "The Puzzling Distribution of the High-Density Molecular Gas in HH 1-2: A Contracting Interstellar Toroid?" Torrelles, J.M., Gómez, J.F., Ho, P.T.P., Rodríguez, L.F., Anglada, G., and Cantó, J. *Ap. J.*, **435**, 290 (1994).

16. "Tidal Shredding of Gaseous Disks among the M81 Triplet," Yun, M.S., Ho, P.T.P., and Lo, K.Y. *Nature*, **372**, 530 (1994).

17. "The Molecular Environment of the HH34 System," Anglada, G., Estalella, R., Mauersberger, R., Torrelles, J.M., Rodríguez, L.F., Cantó, J., Ho, P.T.P., and D'Alessio, P. *Ap. J.*, **443**, 682 (1995).

18. "Line Broadening in the W3(OH) Champagne Flow and Implications for Theories of Massive Star Formation," Keto, E.R., Welch, W.J., Reid, M.J., and Ho, P.T.P. *Ap. J.*, **444**, 765 (1995).

19. "VLA OH Observations of High Negative Velocity Gas Towards Sgr A West — A HIgh-Velocity Cloud Interacting with the Galactic Center," Zhao, J.-H., Goss, W.M., and Ho, P.T.P. *Ap. J.*, **450**, 122 (1995).

20. "Ammonia Maser in a Molecular Outflow Toward W51," Zhang, Q., Ho, P.T.P. *Ap. J.*, **450**, L63 (1995).

21. "SiO Emission in a Jetlike Molecular Outflow toward L1157," Zhang, Q., Ho, P.T.P., Wright, M.C.H., Wilner, D.J. *Ap. J.*, **451**, L71 (1995).

22. "The Molecular Medium of H1413+117: BIMA Array CO(3-2) and HCO+(4-3) Observations," Wilner, D.J., Zhao, J.-H., and Ho, P.T.P. *Ap. J.*, **453**, L91 (1995).

23. "The HII Region Complex G5.48-0.24: Radio Continuum, HI, and CO Observations," Koo, B.-C., Kim, K.-T., Lee, H.-G., Yun, M.S., Ho, P.T.P. *Ap. J.*, **456**, 662 (1996).

24. "High-Velocity Ammonia Emission Associated with the Young Stellar Object Serpens FIRS 1," Curiel, S., Rodríguez, L.F., Gómez, J.F., Torrelles, J.M., Ho, P.T.P., and Eiroa, C. *Ap. J.*, **456**, 677 (1996).

25. "The Central Star Cluster of the Star-Forming Dwarf Galaxy NGC5253," Beck, S.C., Turner, J.L., Ho, P.T.P., Lacy, J.H., and Kelly, D.M. *Ap. J.*, **457**, 610 (1996).

26. "The Thermal Radio Jet of Cepheus A HW2 and the Water Maser Distribution at 0.08″ Scale (60 AU)," Torrelles, J.M., Gómez, J.F., Rodríguez, L.F., Curiel, S., Ho, P.T.P., and Garay, G. *Ap. J.*, **457**, L107 (1996).

27. "Searching for Infall: Aperture Synthesis HCO+(1-0) and SiO(2-1) Observations of the G45.47+0.05 Region," Wilner, D.J., Ho, P.T.P., and Zhang, Q. *Ap. J.*, **462**, 339 (1996).

28. "Search for Optically Thick HII Regions and Ionised Stellar Winds from Lumious Embedded Infrared Sources," Rengarajan, T.N., and Ho, P.T.P. *Ap. J.*, **465**, 363 (1996).

29. "Detection of CO Emission from Dwingeloo 1," Li, J.G., Zhao, J.-H., Ho, P.T.P., and Sage, L.J. *Astron. Astrophys.*, **307**, 424 (1996).

30. "HI and the Maffei 2 Starburst: A Merger Scenario," Hurt, R.L., Turner, J.L., and Ho, P.T.P. *Ap. J.*, **466**, 135 (1996).

31. " Possible Infall in the Gas Disk around L1551-IRS 5," Ohashi, N., Hayashi, M., Ho, P.T.P., Momose, M., and Hirano, N. *Ap. J.*, **466**, 957 (1996).

32. "Heated Gaseous Streamers and Star Formation in Orion," Wiseman, J.J., and Ho, P.T.P. *Nature*, **382**, 139 (1996).

33. "Sub-arcsecond VLA Observations of HL Tau: Imaging the Circumstellar Disk," Wilner, D.J., Ho, P.T.P., and Rodríguez, L.F. *Ap. J.*, **470**, L117 (1996).

34. "The Contracting Molecular Cores E1 and E2 in W51," Ho, P.T.P., and Young, L.M. *Ap. J.*, **472**, 742 (1996).

35. "The Molecular Core Associated with HH25-26 Region: Contraction or Expansion," Verdes-Montenegro, L., and Ho, P.T.P. *Ap. J.*, **473**, 929 (1996).

36. "Efficient Detection of Grown Dwarfs Using Methane-Band Imaging," Rosenthal, E.D., Gurwell, M.A., and Ho, P.T.P. *Nature*, **384**, 243 (1996).

37. "Interferometric Imaging of IRAS 04368+2557 in the L1527 Molecular Cloud Core: A Dynamically Infalling Envelope with Rotation," Ohashi, N., Hayashi, M., Ho, P.T.P., and Munetake, M. *Ap. J.*, **475**, 211 (1997).

38. "Isotopic CO Images near the Young Triple Star GSS 30," Zhang, Q., Wootten, A., and Ho, P.T.P. *Ap. J.*, **475**, 713 (1997).

39. "Rotation in the Protostellar Envelopes around IRAS 04169+2702 and IRAS 04365+2535: The Size Scale for Dynamical Collapse," Ohashi, N., Hayashi, M., Ho, P.T.P., Momose, M., Tamura, M., Hirano, N., and Sargent, A.I. *Ap. J.*, in press (1997).

40. "The Ammonia Core in L723: Hot Spots at the Center of the Quadrupolar Molecular Outflow," Girart, J.M., Estalella, R., Anglada, G., Torrelles, J.,Ho, P.T.P., and Rodríguez, L.F. *Ap. J.*, submitted (1997).

41. "Dynamical Collapse in W51 Massive Cores: NH_3 Observations," Zhang, Q., and Ho, P.T.P. *Ap. J.*, submitted (1997).

42. "A Radio Jet-H_2O Maser System in W75N(B) at 200 AU Scale: Exploring the Evolutionary Stages of YSOs," Torrelles, J.M, Gómez, J.F., Rodríguez, L.F., Ho, P.T.P., Curiel, S., and Vázquez, R. *Ap. J.*, submitted (1997).

43. "Dynamical Collapse in W51 Massive Cores: CS(3-2) and CH_3CN Observations," Zhang, Q., Ho, P.T.P., and Ohashi, N. *Ap. J.*, submitted (1997).