Variability of Deeply Embedded Protostars: A New Direction for Star Formation?

Doug Johnstone  
NRC Canada, Herzberg Astronomy and Astrophysics, 5071 West Saanich Rd, Victoria, BC, Canada  

Abstract

The formation of a star is a dynamic process fed by the gravitational collapse of a molecular cloud core. Theoretical models and observations suggest that the majority of this infalling material settles into a protoplanetary disk before reaching the (proto)star and therefore that disk accretion processes are responsible for the rate at which the (proto)star grows. There is no fundamental reason why infall and disk accretion need to be instantaneously identical. Indeed, even within the disk it might be anticipated that there are regions of strong and weak accretion. Together these facts suggest that (proto)stellar mass assembly should be both secular and stochastic and that the underlying physical processes leading to these time-variable accretion rates should manifest in observable time-dependent accretion luminosity variations.

1. Introduction

Observations of the temporal variability of stars have provided significant physical insight into stellar structure, e.g. internal structure and convection. Recently pulsating pre-main sequence stars have also been identified and compared against star formation and evolutionary models (Zwintz, 2008). Given that deeply embedded protostars are primarily powered by mass infall from the surrounding protoplanetary disk, and that this accretion mass is anticipated to vary in both a secular and stochastic manner, long term monitoring of very young protostars should provide significant physical insight into their evolution and the underlying processes responsible for stellar assembly.

2. Background

The simplest models for the formation of a protostar begin with an isothermal cloud core, perhaps truncated by a bounding pressure (Bonnor, 1956; Ebert, 1955), collapsing from the inside-out. The steady-state infall accretion rate, from the cloud core, is thus explicitly determined by the physical parameters and in the case of the singular isothermal sphere reduces to $\dot{M}_\text{s} \approx \frac{c_s^3}{G}$, where $c_s$ is the sound speed in the core (Shu, 1977). For typical core conditions, this leads to $\dot{M} \sim 10^{-6} \text{M}_\odot \text{yr}^{-1}$. More sophisticated isothermal models typically retain the same order of magnitude for the accretion luminosity but include an initial burst of infall and a later decline (e.g. Foster & Chevalier, 1993). Even the addition of angular momentum and magnetic fields does not significantly affect the cloud infall rate, although the material is often no longer able to stream directly to the central forming protostar (e.g. Terebey, Shu, & Cassen, 1984). Adding confidence to these fiducial calculations, the typical time over which a star accretes most of its mass has been measured to be $\sim 0.5 \text{Myrs}$ (Evans et al., 2009), in reasonable agreement with the above steady-state infall rates.

The predicted accretion luminosity from these models, assuming that the infalling core material makes its way directly to the protostar surface, is significantly higher than that which is observed for the majority of protostars (Dunham et al., 2010; Hartmann et al., 2016). To explain this dichotomy, various episodic accretion processes have been suggested in the literature in order to maintain the time-averaged accretion rate required for the growth of a (proto)star while also yielding a lower accretion rate (and luminosity) over much of the protostellar lifetime. Suggestions for episodic mechanisms include competitive accretion (e.g. Offner & McKee, 2011) and protostellar disk instabilities (e.g. Zhu et al., 2010; Vorobyov & Basu, 2005).

At the 2016 “Star Formation in Different Environments” ICSE conference in Quy Nhon, Vietnam, for which this conference proceeding is a record, a wide variety of talks and posters presented both theoretical and observational evidence for episodic accretion and variability during the protostellar phase. Theoretically, Kuffmeier et al. (2017) presented evidence for both secular and stochastic accretion onto protostellar sink cells created within large simulations of turbulent molecular clouds. On a smaller scale, Lomax et al. (2017) found that only through episodic accretion and applying specific initial kinematic conditions within the originall sing core could protostars form in their simulations and match the known observations. Observationally, Tokuda (2017) presented ALMA observations of complex velocity structure within the L1521F core, suggesting that the initial conditions of star formation can be much more dynamical than the simple isother-
nal models discussed above. As well, Tuan-Anh et al. (2017) determined that the envelope infall rate 140 AU from L527 was a factor of two different than the luminosity-derived accretion rate onto the central star. Considering the evolution of an ensemble of low-mass protostars, Takakuwa et al. (2017) showed that large disks are formed very early during protostellar evolution and that when these disks are observable they already show evidence for structure, such as rings and gaps. Theoretical models for steady accretion through disks do not predict this intricate internal structure. On a different tack, Stecklum et al. (2017) presented time-dependent observations of light-echoes from high-mass young stellar objects, showing specifically the eruptive behaviour of HMYSO S255IR-NIRS3.

3. Observing Strategy

All of these theoretical and observational results support the notion that time variability of protostars is worth further investigation. Furthermore, while the large amplitude accretion events such as the observed FUors and EXors (e.g. Herbig 1977; Hartmann & Kenyon 1996) and the theoretically postulated gravitational instability in disks (e.g. Vorobyov & Basu 2005) may be extremely infrequent, shorter term monitoring provides clues to the accretion processes working in the inner protoplanetary disk where planet formation is expected to take place. To date, only three outbursts have been detected from deeply embedded protostars (Fisher et al. 2012; Safron et al. 2015; Hunter et al. 2017), although indirect evidence for episodic accretion are found in both the shock-bullets seen in protostellar outflows (e.g. Reipurth 1989; Raga et al. 2002) and non-equilibrium chemistry (Kim et al. 2011; Jørgensen et al. 2013).

Variability surveys of embedded protostars need to be performed in the far infrared through the sub-millimetre observations. The optimum wavelength to observe variability in deeply embedded protostars is the far infrared, where the spectral energy distribution peaks. Without an on-going far infrared space mission, however, observations at longer, sub-millimetre wavelengths take centre stage. An international team of astronomers, headed by myself and Greg Herczeg (Kavli, Peking), have obtained time at the James Clerk Maxwell Telescope (JCMT) to survey eight nearby (d < 500 pc) star-forming regions with a 30 arc-minute field of view, at a monthly cadence over three years using the continuum camera SCUBA-2 at 850 μm (Herczeg et al. 2017). Table 1 provides details on the eight regions, including the location, the number of bright sub-millimetre peaks, and a census of known protostars. Figure 1 shows a sample field observed with the JCMT, overlaid with the locations of known protostars and disks.

This JCMT project is very much an exploratory survey and a stringent test of the ability to calibrate sub-millimetre observations. The relative calibration of the JCMT is measured to be ~ 5% (Dempsey et al. 2013) when using the standard data reduction pipeline. We have investigated a variety of techniques for performing ‘self-calibration’ of our observations in order to improve on this value and have settled on a Gaussian clump-fitting analysis both to remove the pointing error of the telescope (leaving less than 1″ residual pointing error as compared to the 15″ beam) and to flux calibrate the fields to better than 3% (Mairs et al. 2017). With one year of observations complete, a data reduction pipeline in place, and a team of dedicated astronomers considering each region carefully, a paper detailing the initial results will be written soon. Furthermore, we are also re-reducing earlier JCMT observations of these same star-forming regions, taken as part of the JCMT Gould Belt Survey (Ward-Thompson et al. 2007), to look for secular variations over multi-year baselines.

4. Conclusions

The mass accretion rate onto forming protostars is very likely to be time-dependent and thus observable through changes in the accretion luminosity of deeply embedded protostars. While there is strong evidence, both theoretical and observational, for large amplitude variations over extended periods of time, little is known about the variability of protostars on shorter timescales. Measuring the amplitude and time variability over month to several year timescales will provide a very powerful input and constraint for mass assembly and viscous accretion models, probing conditions within several AU of the forming protostar.
Variability of Deeply Embedded Protostars

Figure 1. Ophiuchus Field. Image shows 850 µm dust continuum emission. The location of YSOs are overlaid. Green triangles denote deeply embedded protostars while red crosses denote Class II disk sources.

Table 1. JCMT Transient Survey Fields

| Name                  | Location          | SCUBA-2 peak flux/beam | Spitzer Sources Class 0/I | Spitzer Sources Flat | Spitzer Sources Class II |
|-----------------------|-------------------|------------------------|---------------------------|---------------------|--------------------------|
| Persens - NGC1333     | 032854+311652     | > 0.2 Jy 9 5           | 31                        | 13                  | 57                       |
| Persens - IC348       | 034418+320459     | 5 3 2                  | 32                        | 29                  | 158                      |
| Orion A - OMC2/3      | 053531-050038     | 60 30 17               | 11                        | 6                   | 94                       |
| Orion B - NGC2024     | 054141-015351     | 21 9 5                 | 11                        | 12                  | 87                       |
| Orion B - NGC2071     | 054613-000605     | 25 11 4                | 14                        | 5                   | 54                       |
| Ophiuchus             | 162705-243237     | 26 5 2                 | 18                        | 27                  | 60                       |
| Serpens Main          | 182949+011520     | 14 10 7                | 18                        | 10                  | 47                       |
| Serpens South         | 183002-020248     | 20 5 2                 | 47                        | 30                  | 113                      |
Acknowledgments
This work was in part supported by an NSERC Discovery Grant.

References
Bonner, W.B. 1956, MNRAS, 285, 201
Dempsey, J.T., et al. 2013, MNRAS, 430, 2534
Duhman, M.M, Evans, N.J.II, Terebey, S. Dullemond, C.P., & Young, C.H. 2010, ApJ, 710, 470
Ebert, R. 1955, ZA, 37, 217
Evans, N.J.II, Dunham, M.M, Jørgensen, J.K., et al. 2009, ApJS, 181, 321
Fisher, W., et al. 2012, ApJ, 756, 99
Foster, P.N & Chevalier, R.A. 1993, ApJ, 416, 303
Hartmann, L., Herczeg, G., & Calvet, N. 2016, ARAA, 54, 135
Hartmann, L. & Kenyon, S.J. 1996, ARA&A, 34, 207
Herczeg, G. et al. in preparation
Herbig, G.H. 1977, ApJ, 217, 693
Hunter, T.R., Brogan, C.L., MacLeod, G., et al. 2017, ApJL, accepted
Johnstone, D., Hendricks, B., Herczeg, G.J., & Bruderer, S. 2013, ApJ, 765, 133
Jørgensen, J., et al. 2013, ApJ, 779, L22
Kim, H.J., et al. 2011, ApJ, 729, 84
Küffmeier, M., Haugbølle, T., & Nordlund, A. 2017, this volume
Lomax, O., Whitworth, A.P., & Hubber, D.A. 2017, this volume
Mairs, S., et al. 2017 in preparation
Offner, S.S.R. & McKee, C.F. 2011, ApJ, 736, 53
Raga, A.C., et al. 2002, A&A, 392, 267
Reipurth, B. 1989, Nature, 340, 42
Safron, E.J., et al. 2015, ApJL, 800, 5
Shu, F.H. 1977, ApJ, 214, 488
Stecklum, B., Heese, S., Wolk, S., Caratti o Garatti, A., Ibanez, J.M., & Linz, H. 2017, this volume
Takakuwa, S., et al. 2017, this volume
Terebey, S., Shu, F.H., & Cassen, P. 1984, ApJ, 286, 529
Tokuda, K. 2017, this volume
Tuan-Anh, P., Nhung, P.T., Diep, P.N., Hoai, D.T., Phuong, N.T., Thao, N.T., & Darriulat, P. 2017, this volume
Vorobyov, E.I. & Basu, S. 2005, ApJ, 633, 137
Ward-Thompson, D., et al. 2007, PASP, 858, 855
Zhu, Z., Hartmann, L., Gammie, C.F., et al. 2010 ApJ, 713, 1134
Zwintz, K. 2008, ApJ, 673, 1088