Pulsed accretion in a variable protostar

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Periodic increases in luminosity arising from variable accretion rates have been predicted for some pre-main-sequence close binary stars as they grow from circumbinary disks1–3. The phenomenon is known as pulsed accretion and can affect the orbital evolution and mass distribution of young binaries4–6, as well as the potential for planet formation7–9. Accretion variability is a common feature of young stars, with a large range of amplitudes and timescales as measured from multi-epoch observations at optical10–12 and infrared13–15 wavelengths. Periodic variations consistent with pulsed accretion have been seen in only a few young binaries via optical accretion tracers14–16, albeit intermittently with accretion luminosity variations ranging from zero to 50 per cent from orbit to orbit. Here we report that the infrared luminosity of a young protostar (of age about 10 years) increases by a factor of ten in roughly one week every 25.34 days. We attribute this to pulsed accretion associated with an unseen binary companion. The strength and regularity of this accretion signal is surprising; it may be related to the very young age of the system, which is a factor of ten younger than the other pulsed accretors previously studied.

We obtained multi-epoch mid-infrared (MIR) observations of the star forming region IC 348 using the Spitzer Space Telescope. Among the roughly 300 pre-main-sequence objects in the cluster, the protostar LRL 54361 (which we refer to here as L54361) exhibits by far the largest MIR flux variability. We have a total of 81 separate observations of L54361 taken with all three instruments on board Spitzer. The multi-epoch spectral energy distribution (SED) is shown in Fig. 1. The measured bolometric luminosity of the system ranges from about 0.2 to 2.7 solar luminosities (L⊙). The spectral shape remains relatively constant over this range, apart from slightly bluer MIR colours at higher luminosities.

The photometric light curve indicates that the flux variations occur repeatedly throughout the seven-year span of our observations. The two longest contiguous sets of photometry (Fig. 2) reveal a strong pulse signature in which the flux increases by about two magnitudes in as little as a few days, followed by a longer exponential decay over the following few weeks. The combined photometric data set suggests that the variability of L54361 is periodic in nature; the pulse shape revealed by the contiguous warm Spitzer photometry appears in the older data and at other wavelengths, albeit with variations in the pulse width and peak flux. Using several statistical tests, we find that the flux peaks repeat with a robust period of 25.34 ± 0.01 days.

Follow-up multi-epoch imaging taken with the Hubble Space Telescope at near-infrared wavelengths reveals spatially resolved scattered light structures associated with L54361 (Fig. 3). The central source varies with almost the same amplitude and light curve shape at 1.6 μm as seen in the Spitzer data, and the peak occurs exactly as expected given the previously determined period. The geometry of the scattered light is similar to that of other protostars17, and is probably produced by cavities carved out of an infalling envelope by one or more outflows. The apparent motion of the scattered light indicates a light echo produced as the pulse peak light travels through the outflow cavities, and suggests that the source of the illumination is relatively isotropic.

There are three primary sources of periodicity in young stellar objects: stellar rotation, Keplerian rotation of an inner disk, and the orbital motion of a close binary companion. Stellar rotation can manifest itself via localized hot or cool spots, or via interactions between the stellar magnetic field and the outer disk. In the case of L54361, we reject stellar rotation effects on several grounds: (1) rotation periods for pre-main-sequence stars range from a few days to two weeks18 (and protostars are typically faster still19), all lower than the measured period; (2) dark spots produce sinusoidal light curves, with amplitudes of a few tenths of a magnitude in the optical and declining to longer wavelengths; (3) hot spots tend to produce less obvious periodicity owing to the more stochastic nature of accretion, and can exhibit phase-dependent asymmetric illumination of the circumstellar material as they rotate with the star20, which we do not see.

Regarding phenomena related to Keplerian rotation of an inner disk, persistent asymmetric structures such as warps in the inner disk can produce periodic obscuration of both single stars2 and binary systems21,22. We argue that the data are not consistent with this scenario in several respects: (1) obscuration localized to the disk plane would not affect light propagating in the perpendicular direction through the outflow cavity; (2) obscuration events produce characteristic light curve ‘dips’, whereas we see a positive pulse-like shape; (3) as we show below, the MIR and far-infrared flux of L54361 originates from multi-epoch observations of the star forming region IC 348 using the Spitzer Space Telescope. Among the roughly 300 pre-main-sequence objects in the cluster, the protostar LRL 54361 (which we refer to here as L54361) exhibits by far the largest MIR flux variability. We have a total of 81 separate observations of L54361 taken with all three instruments on board Spitzer. The multi-epoch spectral energy distribution (SED) is shown in Fig. 1. The measured bolometric luminosity of the system ranges from about 0.2 to 2.7 solar luminosities (L⊙). The spectral shape remains relatively constant over this range, apart from slightly bluer MIR colours at higher luminosities.

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mostly in the infalling envelope, whose total flux would not be significantly affected by localized stellar obscuration.

The third possibility, a connection to binary motion, is plausible in terms of the length of the period of L54361, although we do not yet have direct evidence of a companion. The pulsed accretion scenario could explain both the shape and amplitude of the light curve. Circumbinary disk simulations consistently show gap-clearing by gravitational torques, followed by accretion streams that feed material onto the central stars. For certain binary architectures, particularly in the case of a highly eccentric orbit, the stellar accretion depends on orbital phase, with the highest accretion rates typically associated with periastron passages. A qualitatively similar process has also been suggested for some X-ray binaries, at least one of which has exhibited optical light curves similar to the MIR behaviour of L54361.

An increase in the accretion luminosity as a result of the binary interaction increases the irradiation heating of circumstellar dust, which then reradiates the energy in the MIR where we observe it. To help test this hypothesis against our observations, we calculated radiative transfer models of protostellar dust emission and scattering. The models include three components that are typical of protostellar systems: infalling envelope, accretion disk and central star. Holding all parameters fixed except for the accretion luminosity, we are able to match the change between SEDs corresponding to two different pulse phases (Fig. 4). The models show a relatively weak wavelength dependence as a function of luminosity, with a slightly flatter spectral slope at about 15 to 70 μm at higher luminosity as a result of optical depth effects in the envelope, in relatively good agreement with the observations.

We do not yet have any direct measure of the central object or its multiplicity status. As our models show, however, the bolometric luminosity provides an estimate of the stellar plus accretion luminosity. Assuming that the low end of the measured range is representative of the stellar luminosity, the combined stellar mass can be roughly estimated by comparing to a theoretical protostellar birthline on an Hertzsprung–Russell diagram. We derive a value of ~0.2 solar masses (\( M_\odot \)); probably an upper limit because some contribution from accretion is likely, although the luminosity may also be somewhat underestimated because of scattering). Conversely, assuming that the upper end of the range of measured luminosity is due entirely to accretion luminosity and adopting the above stellar mass, we derive a maximum mass accretion rate of \( 10^{-6} M_\odot \text{yr}^{-1} \). This is at the upper end of the range of values measured from standard accretion diagnostics. Spectroscopic observations are needed to verify an accretion signature, as well as characterize the binary orbit.

Why L54361 exhibits such a strong and regular signature, unlike the T Tauri-type pulsed accretors observed previously, remains unknown. There may be a connection to its earlier evolutionary stage, in which the infalling envelope provides a steady supply of material to the circumbinary disk. By contrast, T Tauri binaries are older by about a factor of ten, have long since dissipated their natal envelopes, and accrete at lower mean rates. Perhaps stochastic variability from other

Figure 2 | Photometric light curves for L54361. a, b, IRAC 3.6 μm (black) and 4.5 μm (grey, scaled down to match 3.6 magnitudes from the autumn 2009 (a) and autumn 2011 (b) Spitzer observing campaigns. Note that the 3σ photometric uncertainties are equal to or smaller than the symbol size. The dashed line in a marks the observed peak time, which we set as the fiducial epoch for phase = 0. The dashed lines in b mark the predicted peak times assuming a periodicity of 25.34 d. The phased photometric light curve of L54361, assuming a period of 25.34 d and the phase-zero epoch Julian date (JD) 2,455,121.203. Included are measurements taken at three separate wavelengths. Each symbol type represents a contiguous set of photometry: cryo-Spitzer IRAC 3.6 μm (plus signs, asterisk, cross), warm Spitzer IRAC 3.6 μm (filled squares, filled triangles), MIPS 24 μm (inverted triangle, open diamonds, open stars, open triangles), IRS 24 μm (open circles, open squares) and HST WFC3 1.6 μm (filled circles). The 24 μm photometry values are offset by +7.3 mag and WFC3 photometry offset by −5.3 mag to place everything on the same scale.

Figure 3 | Near-infrared images of L54361. a, b, Portions of images taken with HST/WFC3 at 1.6 μm at two epochs corresponding to pulse phases of 0 (a) and 0.3 (b). North is up and east is to the left. L54361 is the extended source just below the center of the images; the point source at upper right is another young stellar object, LRLL 1843. The light from L54361 subtends roughly 14" (~4,000 AU at the distance of the IC 348 region) in a, and about 50" (~15,000 AU) in b. Most if not all of this light is probably the result of scattering off circumstellar dust in the protostellar envelope. An apparent edge-on disk is visible at the center of the object, and three separate structures indicative of outflow cavities extend to the northwest, southwest and northeast. The extent and morphology of the scattered light changes substantially between epochs as a result of the propagation of the pulse peak light. (See Supplementary Information for the complete set of HST images.)
sources such as stellar magnetic interactions or disk turbulence can overwhelm the periodic signature in older stars. It is also possible that the particular orbital parameters of L54361 are rare but more favourable for modulating the accretion flow, such as a very large eccentricity.

Figure 4 Protostellar spectral energy distribution models for L54361. a, b. Comparison of models to two sets of observations roughly representing pulse phases of 0.4 (a) and 0.15 (b). The photometry and spectroscopy are not simultaneous but were selected to correspond roughly to a common flux level. Dashed lines indicate scattering and emission from the infalling envelope; dashed-double-dotted lines represent scattering and emission from the circumstellar accretion disk; dotted lines represent reddened flux from the central star; the solid grey line shows the total flux from all these components. The best-fit parameters include an envelope infall rate of $3 \times 10^{-6} M_\odot\, \text{yr}^{-1}$ (assuming a stellar mass of 0.2 $M_\odot$), envelope centrifugal radius $R_\text{e} = 30$ AU, outflow cavity opening angle $\theta = 30^\circ$, inclination angle of the outflow/stellar rotation axis to the line of sight $i = 70^\circ$, total central luminosity (stellar plus accretion) $L = 0.5 L_\odot$ (a) and 1.3 $L_\odot$ (b), and the fraction of $L$ due to the stellar luminosity $\eta_\text{star} = 0.5$ (a) and 0.19 (b). The only parameter that was actually changed between the two models was $\eta_\text{star}$ with appropriate values so that the stellar luminosity remained constant while the accretion luminosity changed by a factor of $\sim 4$. (See Supplementary Information for details of the model calculations and parameters.)

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