A $\sim0.2$–solar–mass protostar with a Keplerian disk in the very young L1527 IRS system

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In their earliest stages, protostars accrete mass from their surrounding envelopes through circumstellar disks. Until now, the smallest observed protostar-to-envelope mass ratio was about 2.1 (ref. 1). The protostar L1527 IRS is thought to be in the earliest stages of star formation\textsuperscript{2}. Its envelope contains about one solar mass of material within a radius of about 0.05 parsecs (refs 3, 4), and earlier observations suggested the presence of an edge-on disk\textsuperscript{5}. Here we report observations of dust continuum emission and $^{13}$CO (rotational quantum number $J = 2 \to 1$) line emission from the disk around L1527 IRS, from which we determine a protostellar mass of 0.19 $\pm$ 0.04 solar masses and a protostar-to-envelope mass ratio of about 0.2. We conclude that most of the luminosity is generated through the accretion process, with an accretion rate of about $6.6 \times 10^{-7}$ solar masses per year. If it has been accreting at that rate through much of its life, its age is approximately 300,000 years, although theory suggests larger accretion rates earlier\textsuperscript{4}, so it may be younger. The presence of a rotationally supported disk is confirmed, and significantly more mass may be added to its planet-forming region as well as to the protostar itself in the future.

The protostar L1527 IRS (hereafter L1527), at a distance of about 140 pc, is one of the nearest class 0 protostars; this is the earliest phase of the star formation process\textsuperscript{7}, and we show a schematic diagram of a protostellar system in Fig. 1. Observations of dust continuum emission towards L1527 were obtained with the Submillimeter Array (SMA) and Combined Array for Millimeter-wave Astronomy (CARMA) at wavelengths of 870 $\mu$m, 1.3 mm and 3.4 mm, following up indications from previous Gemini results\textsuperscript{8} that L1527 harboured an edge-on disk. The 870-$\mu$m and 3.4-mm data are shown in Fig. 2 with sufficient resolution to resolve the emission from the disk midplane, finding it to be extended north–south, like the 3.8-$\mu$m dark lane. The observed disk is $\sim 180 \pm 12$ astronomical units (AU) in diameter (radius $R = 90$ AU), measured from inside the outer contour plotted in Fig. 2; the dust emission appears smaller than the mid-infrared dark lane because the lower-density outer disk is fainter than the sensitivity limit. (1 AU is the distance from the Earth to the Sun, 1.496 $\times 10^{13}$ cm.) Other studies did not conclusively detect disks around L1527 and other class 0 protostars because the spatial resolution was too low to distinguish the disk emission from the envelope and/or the disks were too small\textsuperscript{9,10}. We estimate a disk mass of $0.007 \pm 0.0007 M_\odot$ from the 870-$\mu$m flux density ($F_{870\mu m} = 213.6 \pm 8.1$ mJy); details are given in Supplementary Information section 3. We consider this mass a lower limit because the adopted dust opacity is large (3.5 cm$^2$ g$^{-1}$ at 850 $\mu$m), and we have not accounted for spatial filtering by the interferometer.

We observed the $^{13}$CO ($J = 2 \to 1$) molecular line transition with CARMA at a wavelength of 1.3 mm. This line traces the outflow in most class 0 protostars\textsuperscript{11}; however, Fig. 3 shows that the $^{13}$CO emission primarily traces the inner envelope and disk in L1527. The outflow is detected at velocities less than $\pm 1$ km s$^{-1}$, but does not affect our analysis (Supplementary Information section 2). The $^{13}$CO data have lower resolution than the 870-$\mu$m and 3.4-mm observations (1$''$, 140 AU); however, the positional accuracy of line emission is comparable to the resolution divided by the signal-to-noise ratio (typically 5 or higher), enabling us to determine the location of emission accurately in each velocity channel. Figure 3 shows the $^{13}$CO emission from the blueshifted and redshifted components to be on opposite sides of protostar, consistent with Keplerian rotation. The emission from the disk is most probably confined to $\pm 1$; at larger radii and lower velocities we expect the flattened envelope to contribute to the kinematics, as shown by lower-resolution $^{13}$CO ($J = 1 \to 0$) observations\textsuperscript{12}. The observations shown in Figs 2 and 3 as a whole provide definitive evidence for a large, rotationally supported disk in this class 0 protostellar system. Such a disk at this early phase may be inconsistent with some disk formation models that consider strong magnetic braking\textsuperscript{12,13}; however, large disks can form at this stage in models with weak magnetic fields\textsuperscript{11,14,15}, or if the magnetic field is not aligned with the rotation axis\textsuperscript{16}.

Assuming that the disk is rotationally supported and that the mass of the protostar is dominant, we can use the position–velocity information from the molecular line data to determine the protostellar mass.

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This has been done for more evolved sources, but not for a class 0 protostar. To determine the mass, we measured the positional offset of the line emission relative to the protostar (1.3-mm continuum source) in each velocity channel (binned to 0.3 km s\(^{-1}\)) and the position–velocity data were fitted with a Keplerian rotation curve (velocity \(v = (GM/r)^{1/2}\), where \(G\) is the gravitational constant, \(M\) is the protostellar mass and \(r\) is the radius at which the velocity is being measured). These data are plotted in Fig. 4 and least-squares fitting yields a protostellar mass of \(0.19 \pm 0.04\ M_\odot\); the flattening of radius at velocities less than \(~1.5\) km s\(^{-1}\) can be attributed to the superposition of rotation velocities projected along the line of sight at large radii. We do not expect contributions from the envelope to affect the fit because its emission is at lower velocities and larger scales\(^1\). The almost edge-on nature of L1527 facilitates this analysis because the \(~85^\circ\) inclination\(^3,9\) does not significantly affect any calculations. Although the model fit in Fig. 4 is simplistic, it highlights the important physics of the problem, and the method is consistent with simulated observations of more complicated line radiative transfer models that require many assumptions (Supplementary Information section 4).

Masses have previously been estimated for binary Class 0 protostellar systems using proper motion measurements at very high resolution\(^20\), but with substantial uncertainty due to unconstrained orbital parameters. The primary uncertainty in our measurement is whether the protostellar mass is dominant over the disk/envelope mass at the scales we are probing. The disk mass of \(0.007\ M_\odot\) could be up to a few times higher owing to opacity uncertainties, and the envelope mass within \(R = 150\) AU is only expected to be \(~0.01\ M_\odot\), because most mass is on large scales. If we allow for a factor of four times higher disk and envelope masses, they would combine to contribute at most \(~35\%\) to the total mass. The kinematic effect of this additional mass should become apparent at larger disk radii, but the current data are insufficient to distinguish this effect. Moreover, the possibility of additional mass would only cause the protostellar mass to be underestimated.

The ratio of protostellar mass to envelope mass in L1527 is only \(~20\%\); all other protostellar systems with dynamical mass measurements from disk rotation have protostellar masses greater than twice the surrounding envelope mass\(^1\). Therefore, in contrast to these more evolved systems, L1527 will probably accumulate significantly more mass. Accreting protostars are expected to follow a ‘birthline’, with rising effective temperature and luminosity with increasing mass; the birthline is also the starting point of pre-main-sequence evolution once the protostar has stopped accreting significantly\(^21\). If L1527 is on the birthline, we can estimate its stellar parameters from the mass. We use the birthline model\(^21\) with an accretion rate of \(2 \times 10^{-6}\ M_\odot\) yr\(^{-1}\) for a \(0.19\ M_\odot\) protostar, this model gives a radius of \(1.7\ R_\odot\), an effective temperature of \(3,300\) K, and a luminosity of \(0.3\ L_\odot\). This indicates that \(~90\%\) of the protostar’s total luminosity \((2.75\ L_\odot)\); ref. 19) is supplied by accretion of mass onto the protostar. Thus, the accretion rate of the disk onto the protostar is \(~6.6 \times 10^{-7}\ M_\odot\) yr\(^{-1}\), assuming \(L_{\text{acc}} = GM\mu M_\ast\) (here \(L_{\text{acc}}\) is the luminosity generated by accretion, the protostellar system. The outflow direction is indicated by the red and blue arrows in a denoting the respective directions of the outflow. The white cross in c marks the central position of the disk from the SMA images. The contours in the 870-μm and 3.4-mm images start at three times the noise level and increase at this interval; the noise level is 5.0 mJy per beam and 0.24 mJy per beam for the SMA and CARMA data, respectively. The ellipses in the lower right corner of each image give the resolution of the observations, approximately 0.25" (a), 0.35" (b) and 0.35" (c). RA, right ascension; dec, declination.
and $R$ is the radius of the protostar). If the protostar has been accreting at this rate throughout its life, its age is only $\sim 300,000$ yr, within the expected lifetime of the class 0 phase$^{22}$. However, theoretical studies indicate that mass infall/accretion rates may be larger initially and decrease with time$^{23}$; in addition, protostars are expected to have variable accretion rates$^{24}$, so L1527 could be younger. The dynamical time of the 0.3 pc outflow (red and blue sides) as measured by a recent survey of the Taurus star-forming region is $\sim 30,000$ yr (ref. 24). This time, calculated from the outflow’s velocity and size, gives an estimate of the age of the outflow, a rough proxy for the protostellar age.

The detection of a proto-planetary disk and a measurement of protostellar mass have made L1527 one of the best characterized class 0 protostellar systems. Its high accretion rate is nearly a factor of 100 greater than those of the more evolved pre-main-sequence stars with disks; this rate is high enough to heat the inner disk to temperatures consistent with early Solar System conditions$^{25}$. Although we cannot say definitively what L1527 will look like at the end of its formation phase, it does have the potential to gain as much mass as the Sun from its envelope and it already has a proto-planetary disk of at least seven Jupiter masses, similar to presumed planet-forming disks$^{26}$. Therefore, L1527 already has all the elements of a solar system in the making.

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Supplementary Information is available in the online version of the paper.

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