

Circumstellar disks of the most vigorously accreting young stars

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Stars may not accumulate their mass steadily, as was previously thought, but in a series of violent events manifesting themselves as sharp stellar brightening. These events can be caused by fragmentation due to gravitational instabilities in massive gaseous disks surrounding young stars, followed by migration of dense gaseous clumps onto the star. Our high-resolution near-infrared imaging has verified the presence of the key associated features, large-scale arms and arcs surrounding four young stellar objects undergoing luminous outbursts. Our hydrodynamics simulations and radiative transfer models show that these observed structures can indeed be explained by strong gravitational instabilities occurring at the beginning of the disk formation phase. The effect of those tempestuous episodes of disk evolution on star and planet formation remains to be understood.

INTRODUCTION

The formation of solar-like systems and binary stars may not simply follow the quasistationary paradigm of classical analytical calculations (1, 2). Instead, protoplanetary disks around these objects might experience an extremely chaotic evolutionary process, whereby vigorous protostellar mass accumulation and disk stabilization happen through inward migration and ejection of large spiral arcs and massive fragments. The observed luminosity of protostars is far less than the expected luminosity inferred from their averaged accretion rate (3). The most promising solution to this apparent paradox is episodic accretion (4, 5), which is supported by the observation of extreme variations (4 to 6 magnitudes) in the optical/infrared brightness of some young stellar objects (YSOs) (6, 7). However, these so-called “accretion outburst” sources are not yet fully understood.

FU Orionis objects, also known as FUors, undergo accretion outbursts during which the mass accretion rate onto the star rapidly increases by a factor of ~1000 and remains there for several decades or more. A sudden increase in the accretion rate heats up the inner disk [$r < 1$ astronomical unit (AU)], observable as enhanced continuum emission at optical and infrared wavelengths. The recent numerical hydrodynamics simulations of collapsing, ~0.1-pc scale, ~1- M_{\odot} (solar mass) cores (8–11) have proposed that, in a short-lived phase after disk formation, mass infall from the collapsing cloud onto the disk usually exceeds mass accretion from the disk onto the protostar. The resulting increase in the mass of the disk destabilizes the disk, leading to the formation of spiral arms and fragments. These gravitationally unstable disks can exhibit FU Orionis–type outbursts when fragments are driven onto the protostar by gravitational interactions with other fragments or spiral arms. In addition, multiple massive ($\leq 0.1 M_{\odot}$) forming fragments may settle in quasistable wide separation orbits or be torqued into the disk inner regions, which naturally explains the detection of massive planets at a broad range of separations from the

host star (8, 9, 12–14). Gravitational perturbations from close encounters with (sub)stellar companions or chance encounters with dense stellar clusters may add to the complexity of structures and can trigger accretion outbursts (15, 16), although these mechanisms can only operate in nonisolated systems. Other outburst triggering mechanisms include the planet-disk interaction (17) and the thermal instability in the inner disk (18, 19). However, the recent discovery of FU-Orionis-type outbursts from Class 0/I YSOs (20–22) seems to require planet formation much earlier than is presently accepted. The thermal instability has difficulty with explaining the observational facts (23, 24); and is now superseded by a more elaborate model combining gravitational instability in the outer disk and the magnetorotational instability in the inner disk (25, 26).

RESULTS

We have performed Subaru-HiCIAO (High Contrast Instrument for the Subaru Next Generation Adaptive Optics) H-band and K-band (that is, 1.6 and 2.2 μm) polarization differential imaging (PDI) toward 4 of the 11 confirmed FUors with optical and infrared outbursts [we refer to a review article (27) for a summary of these sources]: FU Ori, V1735 Cyg (also known as Elias 1-12), V1057 Cyg, and Z CMa (Fig. 1). The obtained linear polarization intensity (PI) images (see the Supplementary Materials section “Polarization differential imaging”) are sensitive to stellar light reflected by tiny amounts of dust. Therefore, these observations provide a powerful tool for understanding the surface morphology of circumstellar disks, picking out relics of interactions without being seriously confused by dominant gas structures, and for identifying residual envelopes surrounding the YSOs. Figure S1 shows the radial intensity profiles for images presented in Fig. 1. We found that in the inner ~1000-AU regions, the measured intensity profiles decrease with radius at rates [$r^{-(1.5 \text{ to } 2.5)}$] that were generally observed in other disks at scales of a few tens to several hundreds of AUs (28–30). However, the radial profile of V1057 Cyg is confused with spiky structures in the outer regions of its envelope. The radial intensity profiles drop less steeply on >1000-AU scales, which can be attributed to the presence of envelope material. The observed systems are likely protoplanetary disks embedded within complicated larger-scale envelopes.

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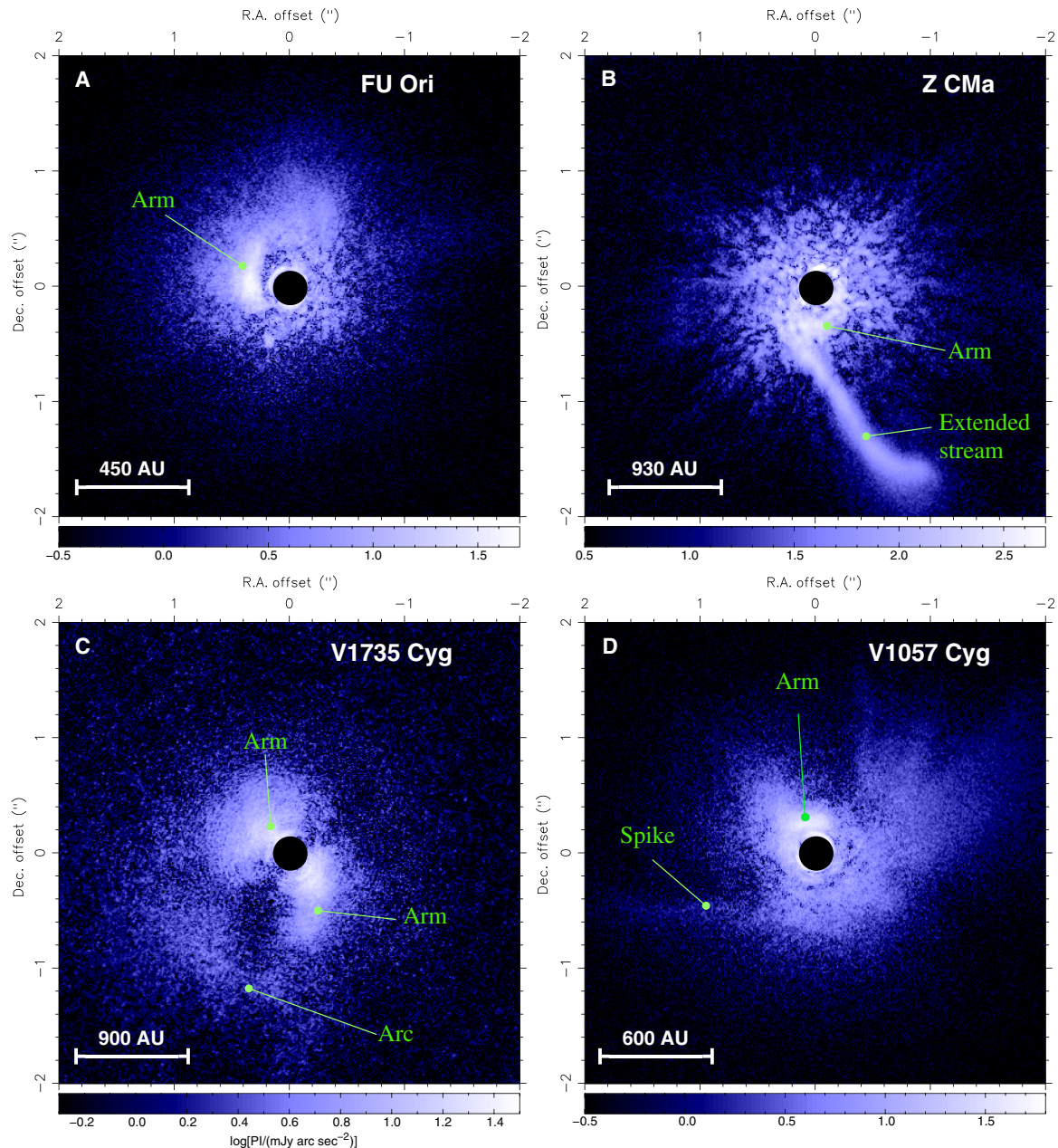


Fig. 1. Polarized intensity images of the selected FU Orionis objects. (A to D) The Subaru-HiCIAO H-band image of FU Ori (A), the K-band image of Z CMa (B), the K-band image of V1735 Cyg (C), and the H-band image of V1057 Cyg (D). Scale bars in (A) to (D) are based on the assumption of distances of 450, 930, 900, and 600 pc. The brightness is presented using a log scale (more in fig. S3). The central $0''.3$ scale region is masked in each panel (see the Supplementary Materials section “Polarization differential imaging”). Annotations of structures are given for convenience; their relations to the distribution of gas are discussed in the main text. R.A., right ascension; Dec., declination; Jy, jansky.

The envelope of V1057 Cyg shows several spikes, connected with filaments on much more extended spatial scales. These extended filaments were interpreted as a result of a relative velocity offset between the protostar and the ambient gas (31).

We resolved a giant arm around FU Ori and its companion, FU Ori S, stretching from east to northeast, at 50- to 500-AU scales. The other three sources are more distant, and therefore, it is more difficult to resolve details. However, asymmetric disk features, which are consistent with giant arms, can be clearly seen in the south of Z CMa, the south-

west and northeast of V1735 Cyg, and the north of V1057 Cyg. More than one arm or gas clump may appear to the west of FU Ori, which can be seen more clearly in the spatially smoothed PI image (fig. S2). The observed spiral arms show polarized intensity contrast of higher than ~ 2 to 5 (Fig. 2). The FU Ori and Z CMa disks are connected with the ~ 1000 -AU scale, approximately radial elongated structures extending to the west and south, respectively. The bright linear feature in Z CMa was also reported in previous observations (32, 33). The PI image of V1735 Cyg has a large-scale arc to the southeast.

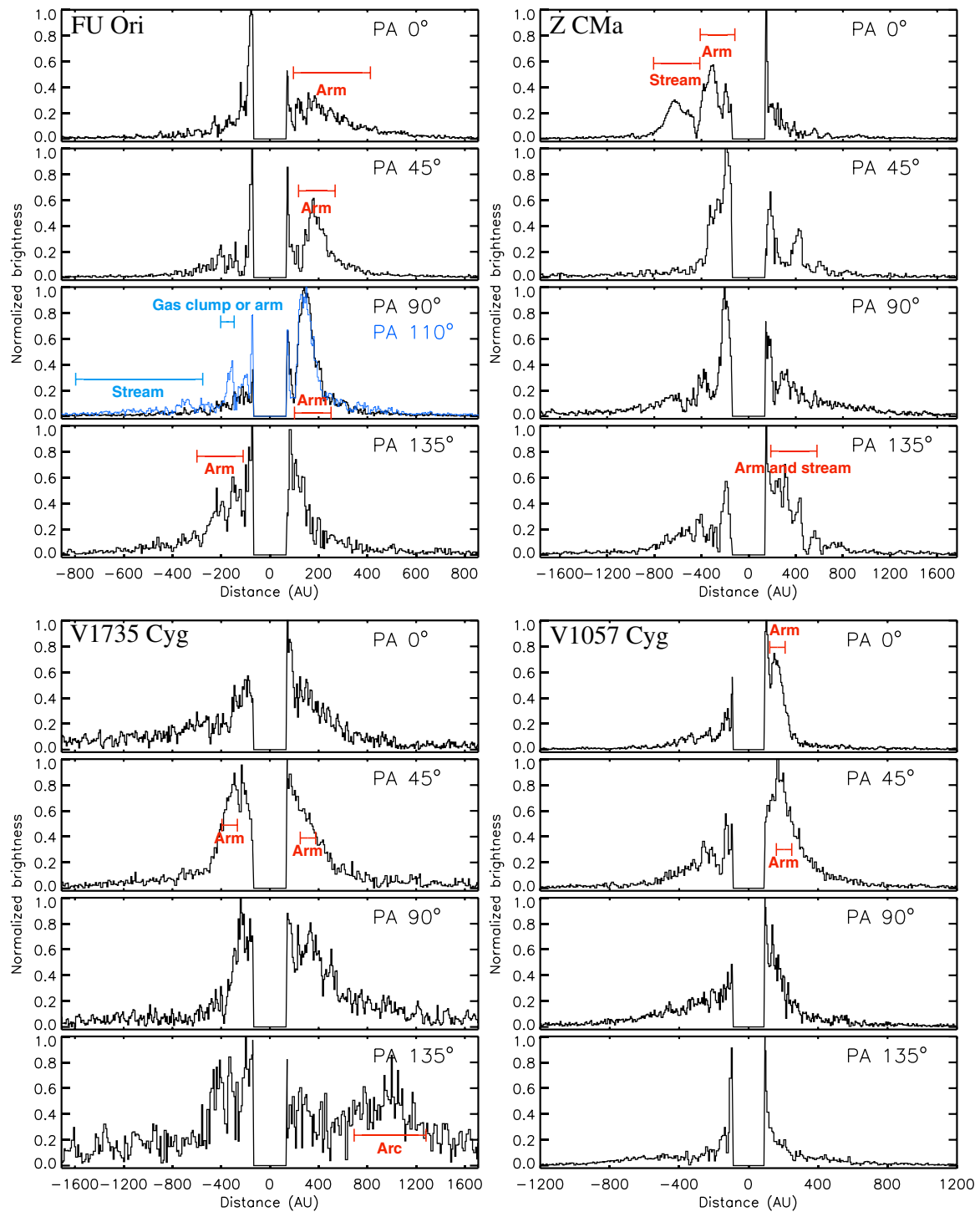


Fig. 2. Slices of the images presented in Fig. 1, at the position angles (measured north through east) of 0°, 45°, 90°, and 135°. An additional slice at the position angle (PA) of 110° is presented for FU Ori to demonstrate the faint and extended elongated structure in the northwest (see also fig. S2). Annotations highlight features from the images.

FU Ori and Z CMa have known close companions (34, 35). The companion of Z CMa is located within our $0''.3$ occultation mask (see the Supplementary Materials section “Polarization differential imaging”). The companion of FU Ori, FU Ori S, may be associated with a small circumstellar disk and thus can be seen in reflected light in our PI image (Fig. 1). To our knowledge, there is no stellar companion within the fields of view shown here for V1735 Cyg or V1057 Cyg, although unseen (sub) stellar companions or massive gas clumps could be obscured by the optically thick disk for all observed sources. The morphologies resolved in our PI images, consisting of a combination of arms, extended envelope features, and elongated structures and companions, are in excellent agreement with the unstable disk accretion scenario and the hydrodynamics simulations discussed earlier (10, 11), which can account for the intense accretion outbursts as well.

Despite the fact that coronagraphic PI observations can provide high angular resolution images with minimized confusion of protostellar emission, it is important to note that the PI images trace the surface morphology of disk rather than the column density of gas. In the framework of hydrodynamics simulations, only the latter is typically elucidated (11). Radiative transfer models of near-infrared reflected light images, based on the simulated density distributions, can provide the link between observations and simulations. Figure 3 shows our simulated PI images based on the numerical hydrodynamics simulations outlined in the Supplementary Materials section “Hydrodynamics simulations and modeling infrared images.” Our procedure to self-consistently estimate local scale height considered thermal balance, the gravity of the central star, and the self-gravity of the disk. The model PI images exhibit several 10^2 -AU spiral arms or arcs, which have linearly polarized H-band ($1.6 \mu\text{m}$) intensity contrasts comparable to our Subaru-HiCIAO observations. In addition, our radiative transfer models reproduce the shape of the spectral energy distributions, which are qualitatively similar to previous observations from infrared to millimeter bands (fig. S5). These results demonstrate that the gravitational instabilities in a forming disk are indeed a plausible mechanism for producing the observed structures in the PI images. One intriguing

aspect from our simulations is that, unlike magnetorotational instabilities, which create inhomogeneities on small spatial scales (36), the gravitational instability scenario discussed here more naturally explains the spiral arms on the observed extended spatial scale and can eject gas clumps or streams, which carry sufficient kinetic energy to pierce the disk and envelope and then leave the system (37). We consider other explanations such as nonaxisymmetric waves on the disk surface or tidally induced disk features to be less probable/general but not strictly forbidden because they may require a large stationary disk to preexist in an earlier evolutionary stage, without developing gravitational instability. In addition, they cannot explain the cases that do not have external perturbers.

Motivated by the results of numerical hydrodynamics simulations, we naturally interpret the large-scale arc to the southeast of V1735 Cyg as an expanding relic ejected from the inner disk because of multiple gravitational interactions (37). The same interpretation may be applied to the ~ 1000 -AU scale elongated structures associated with FU Ori and Z CMa (see fig. S2 for a spatially smoothed image of FU Ori) (38). In the case of Z CMa, the ejected relics may be further swept up by protostellar wind or jet and therefore become a narrow feature closely following the edge of the wind/jet (32, 33).

DISCUSSION

As a summary, the presented Subaru-HiCIAO observations (Figs. 1 and 2) have demonstrated the features in common among four FU Orionis objects in the resolved images: the large-scale asymmetrical structures. These structures appear consistent with those produced by our hydrodynamics simulations (Fig. 4), which suggest a strongly unstable phase in the early evolution of protoplanetary disks.

At this unstable stage, the developing gravitational instability in the accreting disk naturally breaks spatial symmetry, creating spiral arms and clumps, which further lead to time-variable protostellar accretion and FU Orionis accretion outbursts (Fig. 4). These remarkable asymmetric features persist through at least several hundred thousand years of the early disk evolution (10, 11).

The proposed scenario is consistent with the results from a Spitzer and Infrared Space Observatory survey of the $10\text{-}\mu\text{m}$ silicate emission/absorption feature, which proposed that the FU Orionis phase is the link between Class I objects, which remain embedded in the circumstellar envelopes, and naked Class II disks (39). Previous analyses that are based on far-infrared and (sub)millimeter measurements with relatively poor spatial resolutions also claimed association with circumstellar envelopes (40). Our Subaru-HiCIAO near-infrared images are probing circumstellar structures with more than 100 times improved angular resolution over those previous far-infrared and (sub)millimeter observations used for spectral energy distribution analysis. The small innermost working angular scale ($0''.3$) of HiCIAO permitted high angular resolution and high dynamic range images connecting the spatial scales from the circumstellar disk to the envelope. Therefore, these spatially resolved images present a much clearer and robust picture of circumstellar disk and envelope systems than before.

The previous optical and near-infrared imaging observations [see Grady *et al.* (41) and Quanz (42) for up-to-date reviews] did not provide a sample of sources that are undergoing accretion outbursts. Thus, our reported four FU Orionis objects have provided a very different point of view in the context of star formation. In particular, our resolved

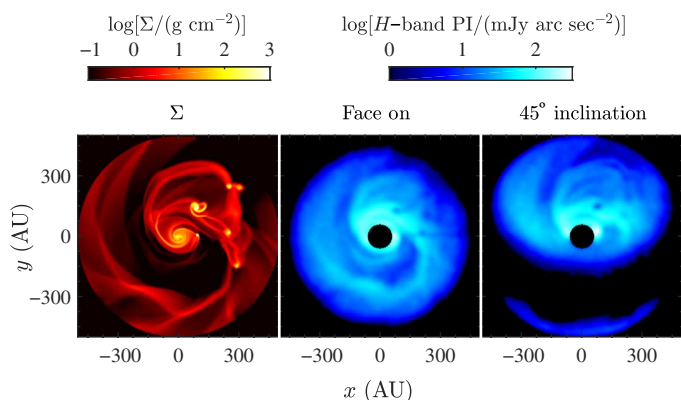


Fig. 3. Radiative transfer models of reflected infrared light from a gravitationally unstable disk. Panels from left to right are the gas column density produced by hydrodynamics simulations, the simulated H-band reflected light image for a face-on projection, and the simulated H-band reflected light image for the case of an inclination of 45° . The image sizes are $1000 \text{ AU} \times 1000 \text{ AU}$. The simulated reflected light images have the same spatial resolution and occultation mask size as our Subaru-HiCIAO image of FU Ori.

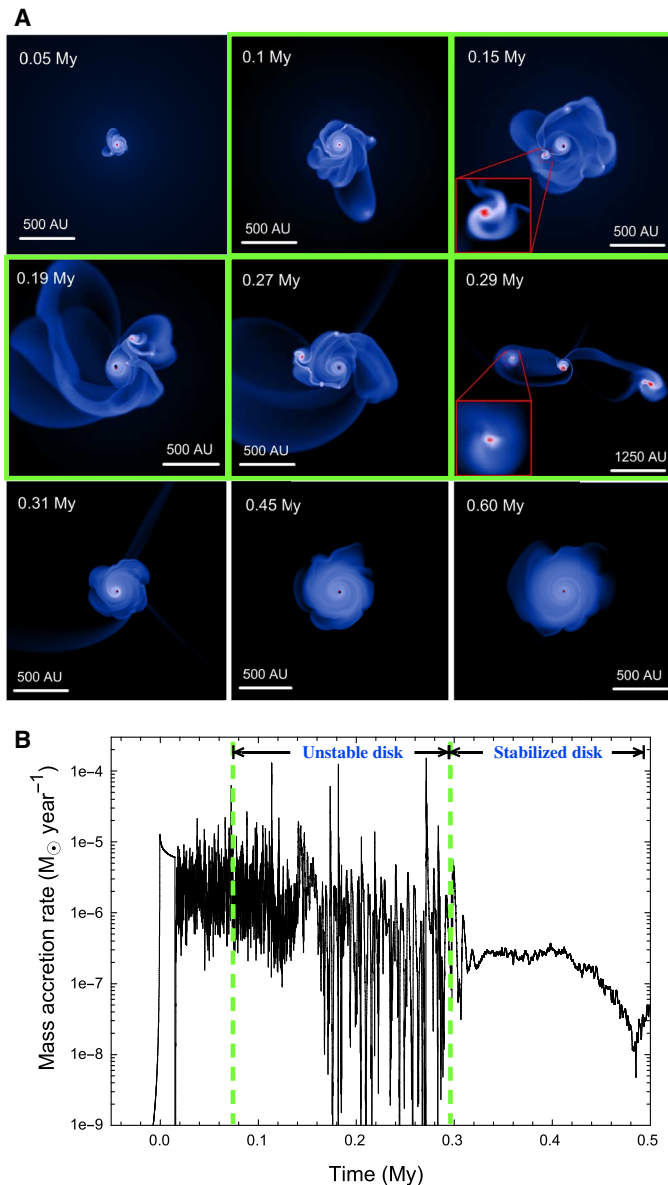


Fig. 4. Numerical hydrodynamics simulation of forming YSO. (A and B) Simulated disk surface density (A) and the protostellar accretion rate (B) over the time period of the simulation. The green boxes in (A) and the time period bound by the green dashed lines in (B) represent the proposed evolutionary stage of our observed YSOs (Fig. 1), when the disk exhibits strong spiral arcs and clumps. The inset panels at 0.15 million years (My) highlight the most massive fragment formed in the simulation. The inset panel at 0.29 My indicates one of the two ejected fragments.

structures are several times bigger than the spiral arms presented in previously observed sources such as MWC 758 and SAO 206462 (43, 44). The latter are typically on the $< \sim 100$ -AU scales, distinct from the large-scale arms as presented in our models (Figs. 3 and 4). For instance, the disk masses of MWC 758 and SAO 206462 are on the order of $\sim 1\%$ of the stellar mass (45). Because of the larger velocity shear on the small scales, it is not easy to trigger gravitational instability for these $< \sim 100$ -AU low-mass disks. Therefore, the discovered features in common

from the presented FU Orionis objects should be considered a missing piece of an overall picture, which helps to understand not only the FU Orionis objects by themselves but also the evolutionary track of YSOs in general (10, 46). The synergy between the presented observations and the hydrodynamics simulations with radiative transfer modeling indicates that the formation and evolution of some, if not all, protoplanetary systems can be more dynamic and chaotic than was previously thought.

Finally, our assertion based on numerical simulations is that the large-scale gravitational instability will naturally occur when the disk is fed by a collapsing envelope, provided that the parental cloud has sufficient mass and angular momentum (8). This gravitational instability and associated disk fragmentation will then episodically trigger protostellar accretion outbursts (Fig. 4). It is therefore important that all four observed objects show features typical of gravitationally unstable disks. Gravitational instability may linger through the quiescent stage, although in the immediate preburst and actual burst phases, it is expected to be the strongest. We note that sources undergoing large-scale gravitational instability, but not temporally undergoing protostellar accretion outburst or even being underluminous, are also reasonable in our proposed scenario. However, resolving asymmetric disk structures for nearby (for example, $d < 450$ pc) YSOs requires $< \sim 0''.1$ angular resolution. Spiral features of Herbig Ae/Be disks can be resolved with the illumination of the relatively luminous host stars. Otherwise, it can be observed with the sources that are undergoing brightness outburst. The optical and near-infrared imaging using the 30-m class telescopes in the near future [for example, the Thirty Meter Telescope (TMT) and the European Extremely Large Telescope (E-ELT)] or the ALMA long baseline observations are required to detect such structures from the lower-mass and the more quiescent, embedded YSOs.

MATERIALS AND METHODS

We performed linear polarization differential imaging in the near-infrared bands toward four FU Orionis objects using the HiCIAO of the Subaru 8.2-m Telescope. Depending on the dust column density of the subjects being observed, these observations can either probe the surface morphology of dense objects (for example, protoplanetary disks) or can penetrate deeper into the more diffused structures. While the observations traced the surface structures of disks, these disk features are intimately connected to the underlying disk density distribution and vertical profiles. We base our interpretation on the numerical hydrodynamics simulations and radiative transfer modeling. Details of our data reduction, numerical simulations, and radiative transfer modeling are provided in the Materials and Methods section of the Supplementary Materials. Our raw observational data will be available on the Subaru-Mitaka Okayama-Kiso Archive System (<http://smoka.nao.ac.jp/>).

SUPPLEMENTARY MATERIALS

Supplementary material for this article is available at <http://advances.sciencemag.org/cgi/content/full/2/2/e1500875/DC1>
Materials and Methods

Fig. S1. Normalized radial intensity profiles (black) of images presented in Fig. 1.

Fig. S2. The smoothed Subaru-HiCIAO H-band image of FU Ori, convolved with a two-dimensional Gaussian kernel with an SD of 5 pixels.

Fig. S3. Polarization images with (A to D) and without (E to H) polarized stellar halo-subtraction. Brightness is log-scaled.

Fig. S4. A schematic representation of the numerical hydrodynamics model, showing the vertical cut through the disk and infalling parental core.

Fig. S5. The simulated spectral energy distributions for the model shown in Fig. 3, based on our hydrodynamics simulations (see the Supplementary Materials section “Hydrodynamics simulations and modeling infrared images”), and the observed spectral energy distribution from FU Ori, Z CMa, V1735 Cyg, and V1057 Cyg (50).

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