A Multi-Wavelength Study of the 2003–2006 Outburst of V1647 Orionis

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The birth of a star is accompanied by the formation of a circumstellar disc which interacts with the star, but most young stars accrete matter at rates that do not influence the mass of the disc on short timescales. However, in so-called FU Orionis stars, a significant fraction of the total disc mass is accreted onto the central star within a short time. During these FU Orionis events, the light generated by accretion outshines the star by up to 6 magnitudes for a period of several years to decades. The star, V1647 Orionis, underwent such an event. We have used FORS2 and NACO on the VLT and TIMMI2 at the ESO 3.6-m telescope to monitor V1647 Orionis from four months after outburst until the system returned to its pre-outburst brightness level, nearly three years later. Our optical photometry and spectroscopy confirm that V1647 Orionis has indeed undergone an outburst whose characteristics resemble those of the FU Orionis stars.

Violent phenomena in young stars

One of the clearest pieces of evidence for disc accretion during early stages of stellar evolution are FU Orionis and EX Lupi outbursts. These outbursts are thought to be the consequence of a sudden and steep increase of the mass accretion rate onto the central star, which changes from those commonly found around T Tauri stars (~ 10^{-7} $M_{\odot}$ yr^{-1}) into values of 10^{-3}–10^{-4} $M_{\odot}$ yr^{-1}. Statistical studies suggest that young low-mass stars experience several FU Orionis-like outbursts during the early phase of stellar evolution. During these rare occurrences, the protoplanetary disc reaches high temperatures (> 1500 K). Interestingly enough, studies of chondritic material – little droplets of rock that have melted and then re-condensed – found in comets have shown that our own Solar System must also have gone through one or more such FU Orionis events early in its lifetime. The mechanism responsible for the disc instability which leads to a FU Orionis event is still unclear.

Observationally, studies of FU Orionis outbursts have been hampered by the low frequency with which they have been detected (the last such event reported in our Galaxy dates from 1984). The emergence of a new pre-main-sequence outburst object is thus a unique opportunity to address the physical processes that occur in the disc's interior.

The appearance of a new nebula in Orion

In late 2003, amateur astronomer J. W. McNeil reported the mysterious appearance of a bright new nebula within the Orion B molecular cloud complex (McNeil et al. 2004). Rapid follow-up observations from several observatories confirmed the existence of extensive bright nebulosity, associated with the previously anonymous young star V1647 Orionis, and never previously detected (see Figure 1). In the months following the discovery, this star showed an increase of its optical/IR brightness of up to 6 magnitudes. The outburst has been observed from the X-ray regime (Grosso et al. 2005) to infrared wavelengths (Muzerolle et al. 2005). In February 2004, four months after the onset of the outburst, the brightness rise stopped and the magnitude remained (relatively) constant. In November 2005, V1647 Ori began to fade fast, returning to its pre-outburst optical brightness level in April 2006.

Using optical imaging and spectroscopy with FORS2 at ESO's Very Large Telescope (VLT), and photometry and spectroscopy in the mid-infrared with TIMMI2 at the ESO 3.6-m telescope, we have monitored the evolution of McNeil's nebula and V1647 Ori from February 2004 until January 2006. In addition, we have performed a more in-depth study of V1647 Ori and McNeil's nebula in the near-infrared using AO-assisted imaging and polarimetry with NACO in April 2005.

Figure 2 shows the light curve of V1647 Ori in the *R*-band based on our new FORS2 data and on previous measurements by other authors. The optical light curve of V1647 Ori can be divided into three parts: i) from October 2003 to February 2004 – the rising period; ii) from February 2004 to August 2005 – the plateau phase; and iii) from August 2005 to January 2006 – the fading period. The rising part is very steep: from October 2003 to January 2004 the optical magnitude increased by more than 3 magnitudes in *R*. From the pre-outburst magnitude level, *R* ~ 23.5, the total rise in brightness of V1647 Ori is larger than 6 magnitudes in *R*. From Figure 1 we find a rate of increase of *R* of ~ 1.5 magnitudes per month. Assuming that this rate

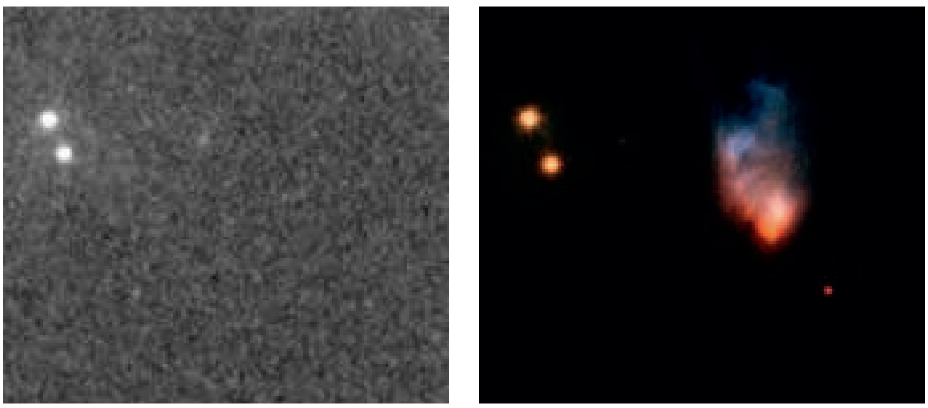

Figure 1: Comparison of the vicinity of V1647 Ori and McNeil's nebula, pre- and post-outburst. **Left:** Pre-outburst Digital Sky Survey image. **Right:** Post-outburst *BRz* colour-composite image obtained with FORS2 on 30 December 2004. Blue, green and red colours correspond to the *B*, *R* and Gunn *z* photometric bands. The dimension of both images is 2.0′ × 1.9′. North is up, East to the left.

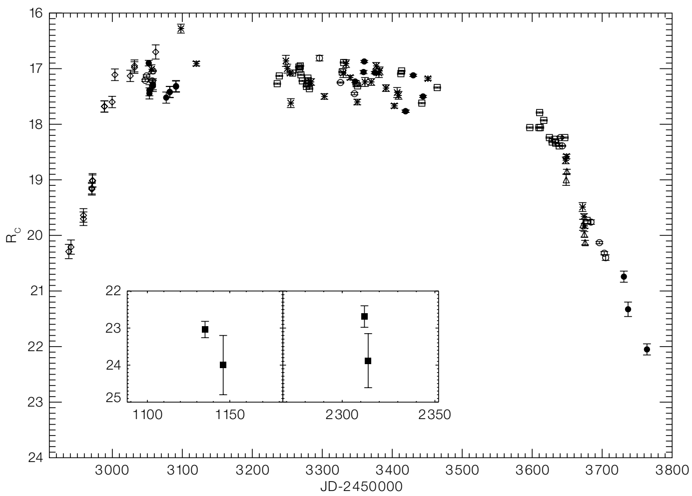

Figure 2: 2003–2006 *R*-band light curve of V1647 Ori. Filled circles show data taken with FORS2, whereas the open plot symbols indicate data taken at other observatories. The insets show the pre-outburst magnitude level of V1647 Ori.

remained constant during all the rising phase, we estimate that the outburst began around the middle of August 2003.

During the plateau phase the optical brightness shows a slow decline with time (ΔR = 0.02 mag/month), on top of which *R* displays a non-periodic, flickered, oscillation on a short timescale. From our data we measure a variation of ~ 0.5 mag between 17 and 18 February 2004. Thus, V1647 Ori at its maximum light shows an optical brightness variation on a time-scale of 24 hours. For five nights we have two consecutive acquisition images (separated by a few minutes) from which we searched for variations on very short time-scales. However, no significant changes in optical brightness are detectable from these measurements. The total duration of the plateau phase is less than two years.

From August 2005 to January 2006, *R* dropped by four magnitudes, indicating the start of the fading period. On 29 January 2006 the last *R*-band measurement taken of V1647 Ori, we estimate *R* = 22.05. From the light curve we estimate a fading rate of ~ 0.8 magnitudes per month during this phase. Assuming a constant fading rate, V1647 Ori thus returned to its pre-outburst brightness at the beginning of April 2006.

The nature of McNeil's nebula

The morphology of McNeil's nebula (Figure 3) resembles that of FU Orionis objects, which often show an arc-like morphology. The nebular emission of such objects mimics the lobes of a bipolar structure, produced by the powerful outflows from the central star. The secondary lobe may be obscured by the circumstellar disc and/or envelope, so that in many cases the nebula appears to have a cometary shape, such as is also seen in V1647 Ori. The emission within McNeil's nebula is not uniform in intensity or in colour. There are two main 'blobs' of higher emission (labelled B and C in Figure 3): the first is close to the star extending to North-West. It is very bright in all bands. The second blob is farther away from the star in direction North-East at a distance of ~ 35″. This structure emits mainly in *B* and *R* bandpasses and is spatially coincident with knot A of the Herbig-Haro object HH 22.

In Figure 3 we show a temporal sequence of images of V1647 Ori and McNeil's nebula in *B*, *R*, *I* and Gunn *z*, taken on 17 February and 20 December 2004 and 2 January 2006. During the first two epochs V1647 Ori was at the maximum light of the outburst (plateau phase). On January 2006 the star was quickly fading returning to its quiescent brightness level. The overall morphology of the nebula (including the substructures B and C) does not show major changes during such a period. Given the FWHM of the FORS2 images (< 0.85″ in *R*) and the nearly two-year time interval, we conclude that no evidence of spatial motion was identified within McNeil's nebula down to a resolution of 0.43″ yr^{-1}, corresponding to an upper limit to the projected expansion velocity of 800 km s^{-1} at the adopted distance toward V1647 Ori of 400 pc.

The temporal evolution of the brightness of McNeil's nebula closely follows that of the outbursting star: the nebular emis-

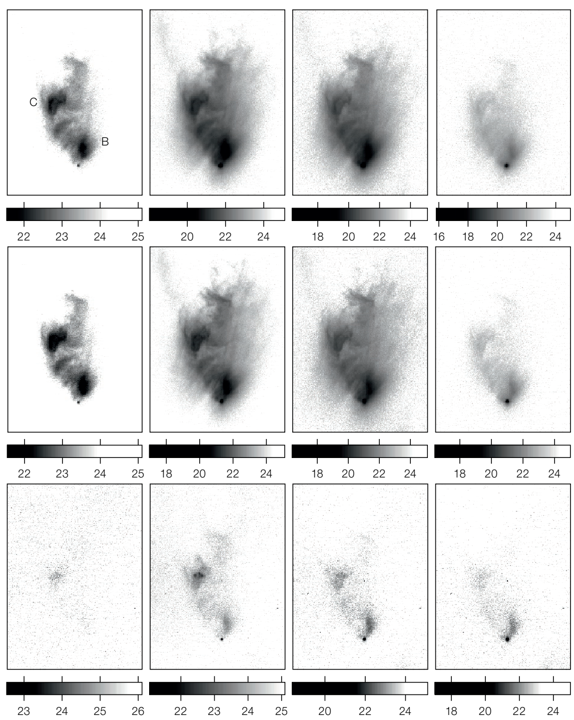

Figure 3: FORS2 images of V1647 Ori and McNeil's nebula taken on 17 February 2004 (top row), 20 December 2004 (central row) and 2 January 2006 (bottom row). The four columns correspond to images in *B*, *R*, *I* and Gunn *z* filters. The intensity scale (bottom of each image) is in mag/arcsec^2.

sion remains unchanged during the plateau phase, as is clear from the top and middle rows of Figure 3. By early 2006 the nebula has mostly disappeared. It is no longer visible in the blue, where also V1647 Ori was not detected up to a limiting magnitude of B > 24.9. A faint emission from blob B and C is still visible in the *R*, *I* and Gunn *z* filters. Given the spatial coincidence with HH 22A, such emission is likely produced by Hα and forbidden lines (all falling in the *R* bandpass) within the Herbig Haro knot.

The close resemblance of the light curve of V1647 Ori and the brightness variations shown by its associated nebulosity strongly suggest than McNeil's nebula is illuminated by light from V1647 Ori that is reflected and scattered by small dust grains within the nebula. In this scenario, the different colours of the nebula would be due to the presence of different amounts of scattering material. Using the method by Magnier et al. (1999) we use the colour dependence of the scattered light to probe the distribution of material inside the nebula. Figure 4 shows the resulting map of the differential extinction in the *V*-band, ΔA_V, for McNeil's nebula. It is clear that the extinction is not uniform in the nebula. Close to V1647 Ori and at the base of the nebula ΔA_V is lower. Moving from the star to the North-East, a region of higher extinction shows up. The total optical extinction in the direction of V1647 Ori caused by material within McNeil's nebula is ~ 6.5 mag. As this estimate does not include foreground extinction, it is a lower limit to the total optical extinction towards V1647 Ori.

The NACO *K*-band polarisation map of V1647 Ori (Figure 5) reveals a compact region of aligned vectors with high degree of polarisation. At larger scales the polarisation pattern is centro-symmetric. Such structures are often seen in near-infrared polarimetric maps of young stars with circumstellar nebulae. These systems show a region of aligned vectors, known as a 'polarisation disc', at the location of the central source, and a gradual transition to a centro-symmetric pattern of vectors in the surrounding nebula. The polarisation disc is attributed to multiple scattering in cases where the optical depth toward the central source is too high for direct observation. The aligned vectors of the polarisation disc are usually parallel to the disc plane. Interestingly, the position angle of the observed polarisation in the vicinity of V1647 Ori (90 ± 9 degrees, Figure 5) is perpendicular to the major axis of the reflection nebula seen in the optical. If the large-scale reflection nebula can be interpreted as being shaped by a wind or outflow from the central star, the polarisation vectors would indeed be aligned with the disc plane.

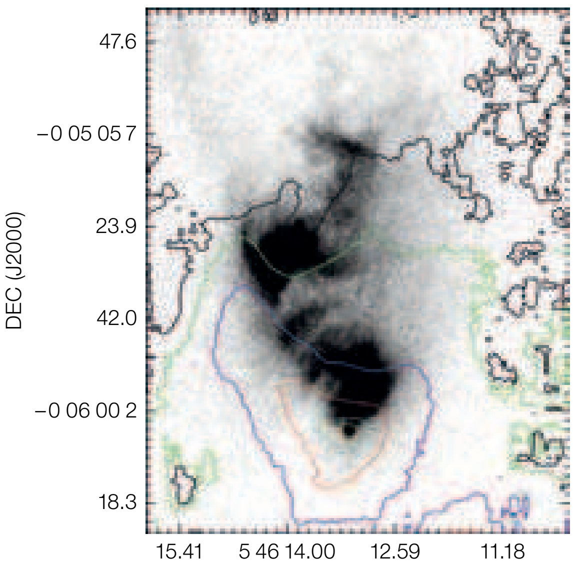

Figure 4: Differential extinction map of McNeil's nebula. The grayscale shows the *V*-band image of the nebula. Overplotted are the ΔA_V contour levels 1.5 (yellow), 2.5 (cyan), 3.5 (red), 4.5 (blue), 5.5 (green) and 6.0 (black). The extinction can be seen to increase gradually as the line of sight from the star to the nebula tilts towards the East.

Optical and mid-infrared spectroscopy

The positive slope of the optical spectrum of V1647 Ori (Figure 6) reveals a red energy distribution of the source. Clearly visible are the Hα and Hβ lines, both characterised by a P-Cygni profile. The He I 5875 Å line and the Na I D1 and D2 doublet are present in absorption and Fe I and Fe II lines in emission are detected in all spectra taken during the plateau phase. The P-Cygni profile of Hα and Hβ is in both cases asymmetric with the emission components lacking the high velocity part. This profile, commonly observed in FU Ori objects and T Tauri stars, can be explained by the presence of an opaque disc which occults part of the red-shifted emission. The profiles of the two lines differ significantly: Hβ has a strong and wide absorption and a weak narrow emission while Hα has strong emission and a weak absorption. In both cases, the blue-shifted absorption shows at least two components: one at −450 km s^{-1}, and the other at −150 km s^{-1}. While the low-velocity component remains almost constant over all the plateau phase, the high-velocity one is variable. In particular, in both lines, the latter shows a progressive decrease in extension from February 2004 to March 2005 until the whole absorption disappears

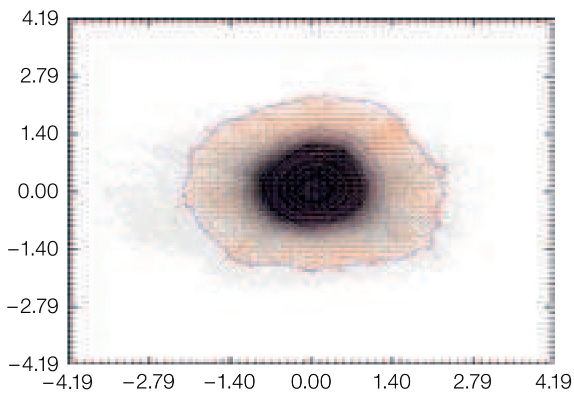

Figure 5: *K*-band polarimetric map of V1647 Ori and McNeil's nebula taken with NACO on 1 March 2006. North is up, East is to the left. Polarisation vectors are superimposed upon total intensity map and contours. Alignment and subtraction residuals are present in the inner region as well as along the diffraction pattern of the telescope. Polarisation values range from 10 to 20 %. The highest values are detected North of V1647 Ori.

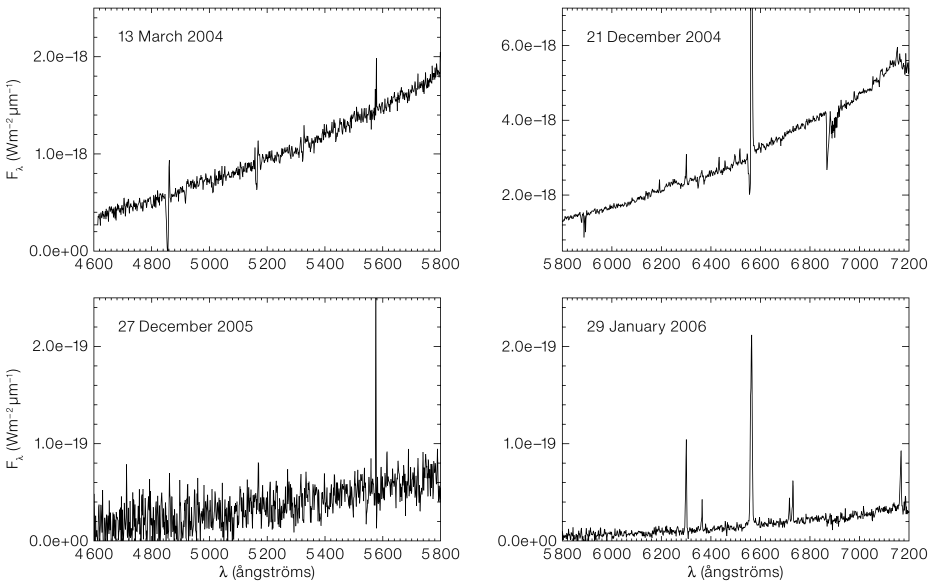

Figure 6: Examples of FORS2 optical spectra of V1647 Ori obtained during the plateau phase (top two panels) and during the fading phase (bottom two panels). *Plateau spectrum:* Clearly visible are Hα and Hβ with P-Cygni profiles, Fe I (5328, 6191, 6494 Å), and Fe II (5169, 6432, 6516 Å) in emission, and absorption from the Na I doublet at 5889 and 5895 Å and the He I line at 5875 Å. *Fading phase spectrum:* No lines are detected in the blue part of the optical spectrum, while the red spectrum is characterised by strong emission lines from Hα, [O I] 6300, 6363 Å, [S II] 6717, 6731 Å and [Fe II] 7172 Å.

in the fading phase spectrum. Furthermore, on three nights (5 January, 18 February and 15 March 2005) the bluest absorption component of Hα is seen in emission. The emission component also varies from night to night, displaying a change in equivalent width and line flux. P-Cygni signatures are also displayed by Fe lines. However, due to the low S/N of the spectra, the absorption component is clearly detected only for the Fe II 5169.08 Å transition.

In contrast to what is observed in the plateau phase, the spectra of V1647 Ori taken during the fading phase also show strong forbidden line emission (see Figure 6), providing evidence for hot (a few thousand K) gas close to V1647 Ori. The emission lines are used as tracers of Herbig-Haro objects, where a collimated jet from the central star collides with the ambient medium. Similar and perhaps newly formed ejecta could be responsible for the forbidden emission lines seen here. None of these forbidden lines were previously detected in the plateau spectrum.

Surprisingly, the outburst of V1647 Ori is also seen at longer wavelengths. Our TIMMI2 data confirm the increased mid-infrared flux: from the pre-outburst level of 0.53 Jy up to 7.6 Jy in the *N*-band on 8 March 2004. The 8–14 µm spectrum is essentially featureless and flat all along the spectral range. Ten months later, in December 2004, the mid-infrared flux of V1647 Ori had dropped by a few Jy. The spectrum is again flat and featureless. Within the accuracy of these measurements (~ 10 %), the flux level remains constant between December 2004 and March 2005. Thus, also in the mid-IR the system experienced a plateau phase. The rapid fading seen in the optical is also experienced by the system in the mid-infrared: on 11 January 2006, the flux level at 12 µm had dropped to 0.9 Jy, still considerably higher than the pre-outburst level. Also in this case the spectrum is flat and featureless.

A consistent model for the 2003–2006 outburst of V1647 Ori

Pre-main-sequence stars are known to be intrinsically variable objects. Commonly observed variability mechanisms include solar-like coronal activity, spots on the stellar surface, stellar pulsation, partial obscuration and subsequent clearing of the line of sight. These processes are however unable to generate the 44 $L_\odot$ luminosity increment produced by V1647 Ori and to produce a six-magnitude burst in the optical lasting for more than two years. To release such an amount of energy, the existence of a secondary luminosity source is necessary. Similar brightening events from FU Orionis stars are explained by a sudden increase of the mass accretion rate from a circumstellar disc onto the central star. The increased accretion rate produces an accretion luminosity which may overwhelm the stellar brightness. Such a process can explain both the dramatic brightening (from X-ray to the infrared) as well as the strong Hα emission observed in the recent outburst of V1647 Ori.

As a consequence of the enhanced accretion rate, a strong wind develops from the disc's surface. The blue-shifted absorption components of Hα and Hβ in the spectrum of V1647 Ori are signatures of this wind. The disappearance of the absorption component in Hα during the fading phase is a confirmation that the strong wind ceased and that the system has been going back to a phase of slow accretion. The accretion disc alone is not able to produce the long wavelength ($\lambda \geq 10$ µm) emission observed, unless it flares strongly over a large range of distance scales. The submillimetre continuum flux during the outburst remained at its pre-outburst level and there are no signatures of flux changes in these wavelength regimes (Andrews et al. 2004). These findings are consistent with the presence of a dusty circumstellar envelope, probably a remnant of the natal cloud which formed V1647 Ori.

Muzerolle et al. (2005) attempt to reproduce the spectral energy distribution (SED) of V1647 Ori by means of a standard viscous accretion disc and of an optically thin envelope. Their model predicts a 10 μm emission feature that is produced by silicate dust grains. However, our multi-epoch mid-infrared spectroscopy reveals a flat and featureless spectrum during the whole outburst duration, which is highly unusual. In FU Orionis objects the silicate feature is seen sometimes in emission and sometimes in absorption. These differences are probably caused by differences in the optical thickness of the system at 10 μm. Our suggestion is that even in the mid-infrared the bulk of the emission is produced by the gas in a dust-free region of the disc, naturally producing a nearly featureless spectrum in the mid-infrared. The emission at longer wavelengths would still be dominated by the dust in the envelope, and therefore not experience the brightness variations associated with the outburst.

Outbursts in pre-main-sequence stars historically have been classified into two main groups, based upon their similarity to the prototypes FU Orionis and EX Lupi (Herbig 1977), depending on outburst duration, maximum magnitude variation and spectral features at maximum light. Since the onset of the outburst of V1647 Ori, it has been debated whether this system is either an FUOR (after FU Orionis) or an EXOR object (after EX Lupi). Table 1 shows that V1647 Ori resembles some aspects of an EXOR (outburst duration, recurrence of the outburst), and some aspects of an FUOR (magnitude rise, SED). However the recurrence timescale of the outburst has an intermediate value between the two classes. The emission line spectrum is clearly distinct from either the absorption line spectrum of an FUOR or the T Tauri-like spectrum of an EXOR (where the H lines show an inverse P-Cygni profile). V1647 Ori may thus be considered an intermediate case between these two classes of objects.

Implications for disc instability mechanisms

A common denominator in all young eruptive stars detected so far seems to be the presence of circumstellar material as well as that of a reflection nebula. These structures are likely remnants of the infalling envelope. The infalling envelope is a potential reservoir of mass for the disc which experiences recursive outbursts. Assuming that the bolometric luminosity during the outburst is dominated by the accretion luminosity, Muzerolle et al. (2005) estimate a mass accretion rate of ~ 10^{-5} $M_\odot$ yr^{-1} for V1647 Ori. Considering the 2–3-year duration of the outburst and the 37-year recurrence timescale, a constant envelope infall rate of ~ 7×10^{-7} $M_\odot$ yr^{-1} is necessary to replenish the disc after each outburst. The disc accretion rate during the quiescent phase is estimated to be ~ 6×10^{-7} $M_\odot$ yr^{-1}.

Submillimetre maps reveal that FU Orionis stars have accretion discs that are larger and more massive than those of T Tauri stars and are comparable in mass to those seen around Class I sources (i.e. young stellar objects with flat or rising infrared spectral energy distribution and which are believed to be in an earlier evolutionary stage than T Tauri stars). The circumstellar material around V1647 Ori accounts for 0.04 $M_\odot$ which is slightly larger than the disc mass of a T Tauri star (~ 0.01 $M_\odot$). All these findings suggest that outbursts *only* occur in Class I sources, when the star is still embedded in the infalling envelope. The outburst duration and mass accretion rate during outburst seem to correlate with the infall rate (see Table 1): objects with higher infall rates have longer outbursts and reach higher accretion rates, while objects with smaller infall rates experience short-lived outbursts. The occurrence of short outbursts might suggest that the envelope is becoming thinner, i.e. that the system is in a transition phase from an embedded Class I source to an optically visible star surrounded by a protoplanetary disc (Class II).

The cause of the 2003–2006 outburst of V1647 Ori, seems clear: a disc instability event occurred in mid-2003, which led to a temporary increase of the mass accretion rate onto the central star. In due time, the disc will be replenished again by infall of matter from the circumstellar envelope and we may expect another outburst of this system around 2040. Our infrared data shows that the disc around V1647 Ori does not appear to be sufficiently massive for its outburst to have been caused by a gravitational collapse of the disc. Instead, our data are consistent with the occurrence of a thermal instability in the inner disc. The presence of a circumstellar envelope around the star/disc system and the outburst statistics of all FUOR and EXOR events suggest that these instability events must be recursive and occur only in a specific stage of the evolution of a young star. At present, the parameter(s) that lead to differences in outburst properties are still unclear, although the mass of the central star and the infall rate from the envelope seem to be good candidates.

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	FUORs	V1647 Ori	EXORs
Outburst duration	> 10 yr	2.6 yr	~ 1 yr
Outburst recurrence	> 200 yr	37 yr	5–10 yr
Mass accreted during outburst	> 10^{-3} $M_\odot$	2.5×10^{-5} $M_\odot$	10^{-6}–10^{-5} $M_\odot$
Magnitude variation	ΔV = 4–6 mag	ΔV = 6 mag	ΔV = 2–5 mag
Outburst accretion rate	10^{-4} $M_\odot$ yr^{-1}	10^{-5} $M_\odot$ yr^{-1}	10^{-6}–10^{-5} $M_\odot$ yr^{-1}
Envelope infall rate	5×10^{-6} $M_\odot$ yr^{-1}	7×10^{-7} $M_\odot$ yr^{-1}	10^{-7}–10^{-6} $M_\odot$ yr^{-1}
Spectral features	F/G supergiant absorption-line spectrum	Emission-like spectrum, P-Cygni lines	T Tauri-like emission-line spectrum

Table 1: Comparison of outburst properties of V1647 Ori with those of FU Orionis objects (FUORs) and EX Lupi type outbursts (EXORs).