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PRE- AND POST-BURST RADIO OBSERVATIONS OF THE CLASS 0 PROTOSTAR HOPS 383 IN ORION

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ABSTRACT

There is increasing evidence that episodic accretion is a common phenomenon in Young Stellar Objects (YSOs). Recently, the source HOPS 383 in *Orion* was reported to have a $\times 35$ mid-infrared—and bolometric—luminosity increase between 2004 and 2008, constituting the first clear example of a class 0 YSO (a protostar) with a large accretion burst. The usual assumption that in YSOs accretion and ejection follow each other in time needs to be tested. Radio jets at centimeter wavelengths are often the only way of tracing the jets from embedded protostars. We searched the Very Large Array archive for the available observations of the radio counterpart of HOPS 383. The data show that the radio flux of HOPS 383 varies only mildly from 1998 January to 2014 December, staying at the level of ~200–300 μJy in the X band (~9 GHz), with a typical uncertainty of 10–20 μJy in each measurement. We interpret the absence of a radio burst as suggesting that accretion and ejection enhancements do not follow each other in time, at least not within timescales shorter than a few years. Time monitoring of more objects and specific predictions from simulations are needed to clarify the details of the connection betwen accretion and jets/winds in YSOs.

Key words: ISM: jets and outflows – radio continuum: stars – stars: formation – stars: protostars

1. INTRODUCTION

The physical mechanisms of gas accretion and ejection are fundamental aspects in the paradigm of low-mass star formation. In its most commonly assumed form, this paradigm requires the quasi-stationary evolution of the forming stars (e.g., Shu et al. 1994). This assumption is seriously challenged by the observational evidence of episodic accretion. First, a handful of individual bursting objects such as FU Ori and EX Lup provide evidence that large accretion bursts in Young Stellar Objects (YSOs) do actually happen, with durations from a few months to ~100 years (e.g., Hartmann & Kenyon 1996; Herbig 2008, Audard et al. 2014). Second, surveys show that YSOs are systematically underluminous with respect to the expectation of steady-accretion models (e.g., Evans et al. 2009; Kryukova et al. 2012). Episodes of significantly increased accretion would alleviate this discrepancy (e.g., Vorobyov 2009; Zhu et al. 2009). Third, episodic accretion in protostars—or class 0 and I YSOs—has also been invoked to explain the observed spread of the Herzprung–Russell diagram of young star clusters (Baraffe et al. 2012).

Although time monitoring campaigns are revealing a large diversity of variation phenomena in YSOs (e.g., Costigan et al. 2014; Günther et al. 2014), it is still not clear whether or not accretion bursts are a widespread phenomenon in YSO evolution. The evidence is particularly scarce for the case of protostars. Only a few class I or young class II objects have been reported to show infrared bursts related to accretion (e.g., Reipurth & Aspin 2004; Caratti o Garatti et al. 2011; Covey et al. 2011; Fischer et al. 2012; Muzerolle et al. 2013).

Recently, Safron et al. (2015) reported an impressive outburst in the embedded object HOPS 383 in *Orion*. This object was classified as a protostar in the *Spitzer* survey presented in Megeath et al. (2012) and in the *Herschel*+*APEX* survey presented in Stutz et al. (2013). Based on the ratio of submillimeter-to-bolometric luminosity and in the characteristic temperature of the spectral energy distribution, Safron et al. (2015) conclude that the object is a class 0 YSO, making HOPS 383 the youngest protostar known with an accretion-related burst. The outburst is most notably seen at a wavelength of 24 μm, in which the brightness increased by a factor $\times 35$ from 2004 to 2008. From their extensive IR to submillimeter follow up, Safron et al. (2015) find no evidence for significant fading of HOPS 383 up through 2012.

Radio observations are a key tool to study YSOs: the thermal free–free emitting radio jets are often the only way to probe the bipolar ejection of material close to the protostar in the optically obscured class 0 objects (e.g., Rodríguez 1997; Anglada et al. 1998). Radio observations are also useful to probe non-thermal (gyro)synchrotron radiation from active YSO magnetospheres (e.g., Güdel 2002; Forbrich et al. 2007). Systematic studies of YSOs show that emission at ~3.5 cm and its variability in class 0 and I protostars is dominated by the free–free radio jets, while in more evolved class II and III YSOs this emission is dominated by the magnetospheric (gyro) synchrotron emission (Dzib et al. 2013; Liu et al. 2014), with possible contributions from disk photoevaporation (Galván-Madrid et al. 2014) or weak radio jets (Rodríguez et al. 2014).

In the standard model of star formation, the magnetohydrodynamical (MHD) launching of jets provides for part of the necessary release of specific angular momentum. The amount of ejected material is usually taken to be a constant fraction of the accreted material (e.g., Pudritz et al. 2007; Shang et al. 2007). There is some observational evidence for this assumption to hold in samples of relatively massive, optically visible YSOs (Frank et al. 2014 and references therein), but it has yet to be tested in the most embedded objects and in time domain. A good way of doing this test in embedded class 0 objects is to look for possible correlations between the free–

Table 1
Data Summary

Epoch	Frequency (GHz)	Array, HPBW, PA (arcsec × arcsec; deg)	Phase Center (h:m:s; deg:arcmin:arcsec)	HOPS383 Offset (arcsec)	rms Noise[a] (μJy beam^{-1})	Flux Density[b] (μJy)
15.01.1998	8.46	D; 9.2 × 7.5, −17.8	05:35:24.395; −05:01:07.27	111.1	42	230 ± 50
14.03.2008+01.06.2008	4.86	DnC+C; 6.0 × 4.2, 49.8	05:35:24.400; −05:01:43.25	138.2	56	<224
14.03.2008+01.06.2008	8.46	DnC+C; 4.8 × 3.1, 57.4	05:35:24.413; −05:00:07.25	82.2	47	<188
13.08.2011	4.87	A; 0.64 × 0.42, −4.6	05:35:23.420; −05:01:30.52	137.8	10	270 ± 20
13.08.2011	7.42	A; 0.44 × 0.27, −3.6	05:35:23.420; −05:01:30.52	137.8	11	310 ± 20
27.10.2014	10.0	C; 2.18 × 1.66, −1.9	05:35:23.480; −05:01:32.30	138.5	13	222 ± 12
03.11.2014	10.0	C; 2.04 × 1.81, −7.2	05:35:23.480; −05:01:32.30	138.5	15	267 ± 16
06.12.2014	10.0	C; 2.29 × 1.70, −28.3	05:35:23.480; −05:01:32.30	138.5	11	293 ± 13
13.12.2014	10.0	C; 2.35 × 1.61, −11.1	05:35:23.480; −05:01:32.30	138.5	13	289 ± 15
15.12.2014	10.0	C; 2.28 × 1.65, −29.3	05:35:23.480; −05:01:32.30	138.5	10	246 ± 10
All 2014	9.81	C, 2.32 × 1.62, −14.1	05:35:23.480; −05:01:32.30	138.5	6	260 ± 6

Notes.
[a] rms noise corrected for primary-beam attenuation around the position of HOPS 383: $\alpha = 5^h35^m29^s.81$, $\delta = -4°59'51''.1$ (Safron et al. 2015).
[b] Flux density of HOPS 383 corrected for primary-beam attenuation. The errors are only statistical, resulting from the noise in the maps and the quality of the fit. The absolute uncertainty of the VLA flux scale is a few percent (Perley & Butler 2013). Upper limits in the 2008 epoch are 4σ.

free emission from radio jets and accretion signatures as seen in the near- to mid-infrared. Bursting protostars offer a unique opportunity to perform this test under different conditions in a given object.

In this Letter, we report on pre- to post-burst centimeter wavelength observations of the bursting class 0 YSO HOPS 383.

2. DATA SETS AND BASIC RESULTS

To analyze the time behavior of HOPS 383 at centimeter wavelengths, we looked for the available observations in the Very Large Array[5] archive. In none of these observations is HOPS 383 at the phase center; however, it falls inside the field of view, allowing the determination of its parameters after correction for the primary beam response. In the following subsections we describe the observation epochs. Table 1 summarizes the relevant properties of the data.

In all the epochs the position of the radio source matches within $0''.3$–$1''.7$ with the infrared position reported by Safron et al. (2015): $\alpha(J2000) = 5^h35^m29^s.81$, $\delta(J2000) = -4°59'51''.1$. This is a fraction of the synthesized beam in all the epochs in which the radio source appears unresolved (see Table 1), and about the synthesized beam size for the 2011 epoch with subarcsecond angular resolution.[6] Since the next closest radio detection is $\approx 120''$ away, and the *Spitzer*-MIPS angular resolution is $\sim 6''$, we conclude that the radio detection here reported is the counterpart of the bursting protostar reported by Safron et al. (2015).

2.1. 1998

These observations were made on 1998 January 13 as part of the project AR387. The analysis has been presented and discussed in Reipurth et al. (1999). The data were obtained at a frequency of 8.46 GHz in the D configuration. Reipurth et al. (1999) do not report a radio counterpart to HOPS 383, most probably because they adopted a stringent limit of 5σ to consider a detection. Our reanalysis of these data shows a faint source with flux density of 0.23 ± 0.05 mJy that coincides spatially with HOPS 383.

2.2. 2008

These observations were made on 2008 March 14 and June 1 in the C and DnC configurations at 4.86 and 8.46 GHz as part of project AT359. The data from the two epochs were concatenated for increased sensitivy, but a counterpart to HOPS 383 was not detected with a 4σ upper limit of 0.22 and 0.19 mJy at 4.86 and 8.46 GHz, respectively.

2.3. 2011

These observations were made on 2011 August 13 with the upgraded Jansky Very Large Array (JVLA) in the A configuration under project 11A-220. The tuning is centered at 4.81 and 7.42 GHz, with total bandwidths of approximately 1 GHz. This is the only epoch with subarcsecond angular resolution. The source associated with HOPS 383 is for the first time resolved into two components (SE and NW) with a separation of $\approx 0''.45$ and joined by a ridge of faint emission. In maps done with (u, v) weighting close to natural, we measure flux densities that are consistent with rest of the detections at other epochs: 0.27 ± 0.02 at 4.81 GHz and 0.31 ± 0.02 mJy at 7.36 GHz (see Table 1). The spectral index between these frequencies is 0.3, indicating free–free emission with low optical depth. Figure 1 shows a map at 7.36 GHz done with weighting between natural and uniform to maximize angular resolution. The double nature of the radio source is clearly seen, probably from a bipolar radio jet or a binary. This map with the highest angular resolution already suffers from significant ($\sim$50%) flux filtering of extended emission.

2.4. 2014

The five more recent observations were made with the upgraded JVLA centered at a rest frequency of 9.81 GHz (3.0 cm) during 2014 October–December. These observations are part of project 14B-230. At that time the array was in its C configuration. The total bandwidth of the continuum observations was about 4.0 GHz. The individual flux densities determined for the five epochs are listed in Table 1, as well

[5] The National Radio Astronomy Observatory is operated by Associated Universities, Inc. under cooperative agreement with the National Science Foundation.
[6] The distance to the IR position in this epoch is $0''.5$ to the centroid of the radio emission, and $0''.3$ to the brightest SE peak.

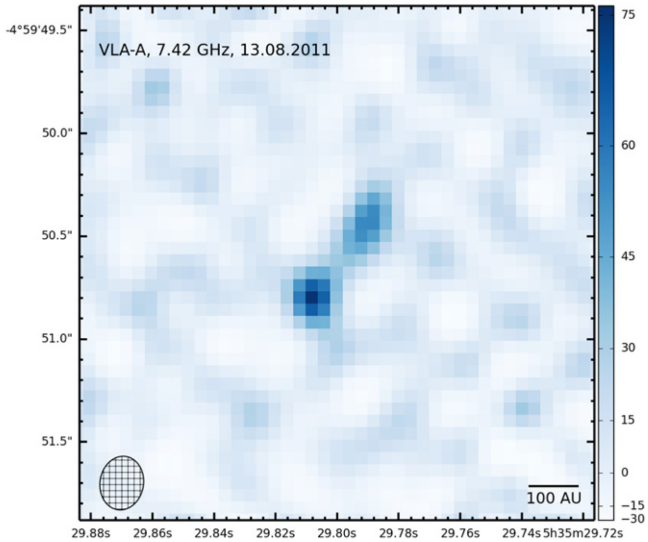

Figure 1. High angular resolution JVLA image of the radio counterpart of HOPS 383, observed on 2011 August 13, and centered at 7.42 GHz (4.0 cm). HPBW = 0″26 × 0″21, PA = −9°0. The target clearly has two components. The peak insensities of the SE and NW components are 75and 55 μJy beam^{-1}, respectively. The rms noise is 11 μJy beam^{-1}.

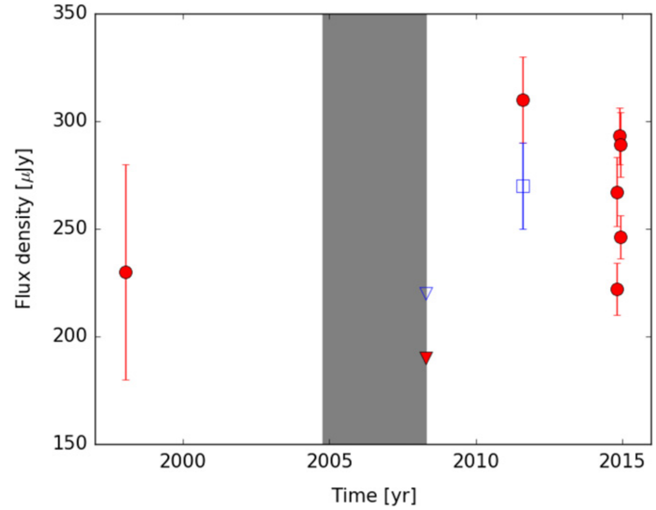

Figure 2. Radio light curve of HOPS 383. The red dots and inverted triangles are X-band (8–10 GHz) measurements and upper limits, respectively. The blue symbols are in the C-band (4–5 GHz). Error bars are $\pm 1\sigma$. See Table 1 for details of the observations. The vertical gray stripe marks the period of time that Safron et al. (2015) estimated for the occurrence of the infrared burst.

as the flux density from the concatenated data. There appear to be marginal flux variations within 2014. The maximal flux density is 293 ± 13 μJy on 2014 December 12, which is 71 ± 18 μJy above the minimal value of 222 ± 12 μJy on 2014 October 27. Then, without considering the few percent uncertainty in the absolute flux scale (Perley & Butler 2013), the largest flux difference within 2014 is significant at 4σ. We also tested for intra-day variability by splitting each of the five observing epochs into two time chunks. In four of the five epochs, the flux measured in each halve of the data is within 1σ of the flux reported in Table 1. In the 2014 November 3 epoch, the fluxes in the halved data are within 2σ of the epoch average, and this is the noisiest of the 2014 observations. We discard significant intra-day variability. These results are consistent with the relatively long variation timescale expected for the radio emission of class 0 YSOs, compared to class II and class III (Liu et al. 2014). Finally, the high sensitivity of these JVLA observations allowed the data to be split into smaller frequency chunks. We made images from the concatenated data in four windows, each 1 GHz wide. The intra-band spectral index of HOPS 383 is consistent with 0, indicating optically thin free–free emission.

3. DISCUSSION

3.1. No Radio Counterpart to the Infrared Burst

MHD-launched jets that load with them a fraction of the accreted material are a basic feature of star formation models (e.g., Pudritz et al. 2007; Shang et al. 2007). Furthermore, there is increasing evidence that this is the case even for the youngest systems: the class 0 protostars (e.g., Li et al. 2014). In these deeply embedded objects, free–free emission from radio jets is one of the best ways to trace the outflowing material in the inner few hundred AU (Rodríguez 1997; Anglada et al. 1998). The origin of the radio emission is often considered to be shock-ionized gas (Anglada 1996), but models that include X-ray ionization within the X-wind scenario also reproduce the observed properties of radio jets (Shang et al. 2004). Regardless of the detailed jet emission mechanism, in the models it is assumed that an increase of accretion is followed by an ejection enhancement. Therefore, if the mid-IR burst truly traces a burst of accretion (Safron et al. 2015), then a significant increase in the radio flux should follow.

We find that in HOPS 383 the infrared burst does not have a counterpart in the radio. Figure 2 shows the radio light curves. The long-term (decadal) radio flux densities show mild variations, staying at a level of ∼200–300 μJy. The earliest 1998 flux density is the same within 1σ with the latest 2014 measurements (Table 1). The average flux density of the detections in the X band (8–10 GHz) is $S_X = 265$ μJy, with a dispersion of 28 μJy, or about the noise in single epochs. Taken at face value, it may even seem that during the IR-burst the radio flux has a minimum (see Figure 2). We constrain the significance of a possible radio flux decrease in 2008 by considering the non-detection in this epoch to have a flux between 0 and the 4σ upper limit. The hypothetical flux decrease between the 1998 detection and the 2008 non-detection has a significance between 3.3σ and 0.6σ. The hypothetical flux increase between 2008 and 2011 (the epoch with the maximum flux) has a significance between 6.0σ and 2.3σ. These estimates do not include the absolute flux uncertainty of a few percent. In the following subsections, we discuss several possible explanations for our result. These possibilities do not necessarily exclude each other.

3.2. Protostellar Accretion and Ejection Variations Are Not Correlated in General

Accretion rates and jet/wind ejection rates have been shown to be correlated within samples of the relatively evolved class II YSOs and FU Orionis objects (e.g., Hartigan et al. 1995; Calvet et al. 1998). However, the idea that in a given object accretion and ejection follow each other in time has only started to be tested. Contrary to the simplest expectations, it may be the case that they do not follow each other. Ellerbroek et al. (2014) could not establish a relation between outflow and accretion variability in the Herbig Ae/Be star HD 163296, the former being measured from proper motions and radial velocities of the jet knots, whereas the latter was measured from near-infrared photometric and Brγ variability. Similarly, Connelley & Greene (2014) monitored a sample of 19 embedded (class I) YSOs with near-IR spectroscopy and found that, on average, accretion tracers such as Brγ are not correlated in time to wind tracers such as the H_2 and [Fe II] lines. The non-detection of a radio burst in HOPS 383 counterpart to the mid-IR burst is consistent with the above mentioned observational results.

Numerical simulations that include the time-variable evolution of protostars can give insight on the possible time correlation of accretion and ejection. Some 3D MHD simulations (e.g., Romanova et al. 2009) have been performed with enough detail to follow the causal connection between protostellar accretion and jets+winds, but they follow the evolution of the system for timescales that are somewhat short compared to our observations and to FU-Ori like bursts in general. Rather large, long bursts such as that observed in HOPS 383 are more likely the result of such processes as gravitational instabilities within the massive young circumstellar disk (e.g., Vorobyov & Basu 2015), but these simulations do not yet resolve the physics of jet/wind production. Further work needs to be done to simulate what happens to the outflows in protostars with large accretion bursts.

3.3. Protostellar Accretion and Ejection Variations Are Not Correlated in Large Bursts

Jets are launched through MHD processes that require the presence of an ordered magnetic field at the stellar-radii scale of the magnetosphere (Shu et al. 1994) and/or further out to a significant fraction of the disk (Konigl & Pudritz 2000). If in a bursting YSO the accretion rate becomes too high, it is possible that the configuration of the magnetosphere and the disk magnetic field become disrupted such that the launching of a collimated jet/wind is shut off (Hartmann 1998). This "jet-quenching" idea needs to be explored in detail in simulations.

3.4. The Interpretation of the Tracers

The final possibility that we consider is that either or both of the assumptions that the radio continuum traces free–free emission from a jet and that the mid-IR burst is due to an enhancement of accretion are incorrect. We argue that this is not the case. (Gyro)synchrotron emission from magnetospheres is known to contribute significantly in the more evolved class II and III YSOs (e.g., Forbrich et al. 2007), but in class I and especially class 0 YSOs the radio emission is most likely dominated by the jet (e.g., Dzib et al. 2013; Liu et al. 2014). Furthermore, the spectral indices measured in the most sensitive epochs are consistent with free–free emission (see Sections 2.3 and 2.4). Regarding the mid-IR burst, although the largest flux increase is at a wavelength of 24 μm, Safron et al. (2015) showed the occurrence of brightening from the near-IR to the submillimeter, making the case for a large ($\sim\times 35$) increase in bolometric—and therefore accretion—luminosity.

A different instance of a misinterpretation of the observations would happen if the mid-IR burst and the radio emission arise from the different components of a binary system. Indeed, from Figure 1, the radio emission can be interpreted as either a bipolar jet or a binary, with the features separated by $\approx$190 AU ($0\farcs45$ at a distance of 414 pc, Menten et al. 2007). However, even if the target is a binary, the lack of a large increase in the combined (unresolved) radio flux at any epoch remains to be explained.

Finally, it is also possible that there was an ejection event traced by a radio jet (as suggested by the morphology in the epoch that resolved the source; see Figure 1), but that the total flux density of the jet features did not have large variations. Based on a measurement of the proper motions in the lobes of the radio jet in IRAS 16293–2422, Pech et al. (2010) inferred a recent bipolar ejection from this source. Interestingly, the total flux density at 8.5 GHz added over the lobes reported by those authors only increased by ∼40% from 2003 to 2008. A large increase in the radio flux could rapidly fade if the ionized material recombines without further ionization. This could happen if some material is dense enough and gets shadowed from the ionizing source[7] (e.g., Galván-Madrid et al. 2011). If the possibility discussed here is correct, then time monitoring should be done at high angular resolution.

4. CONCLUSIONS

Our search in the VLA archive for a cm radio counterpart to the infrared burst recently reported in the class 0 YSO HOPS 383 yielded a negative result. The lack of a counterpart in the radio jet to the accretion burst suggests that accretion and ejection variations do not follow each other in time, at least not for large (∼×35) accretion enhancements and within short (up to a few years) periods of time.

Our observations are consistent with recent reports, using different techniques, of a lack of temporal correlation between accretion and jet/wind tracers in class I YSOs (Connelley & Greene 2014) and a Herbig Ae/Be star (Ellerbroek et al. 2014). We discussed possible interpretations to these observations in the context of the available models. Time monitoring of more sources and more specific model predictions are needed to clarify the details of the connection between accretion and jet/wind ejection in YSOs.

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[7] The recombination timescale for gas with electron density $n_e \sim 10^6$ cm^{-3} is only one month.

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