Results from DROXO

IV. EXTraS discovery of an X-ray flare from the Class I protostar candidate ISO-Oph 85

D. Pizzocaro, B. Stelzer, R. Paladin, A. Tiengo, G. Lisino, G. Novara, G. Vianello, A. Belfiore, M. Marelli, D. Salvetti, I. Pillitteri, S. Sciortino, D. D’Agostino, F. Haber, M. Watson, J. Wilms, R. Salvaterra, A. De Luca

1 INAF-Istituto di Astrofisica Spaziale e Fisica Cosmica Milano, via E. Bassini 15, 20133 Milano, Italy
e-mail: D. Pizzocaro, pizzocaro@lambrate.inaf.it
2 Universit degli Studi dell’Insubria, Via Ravasi 2, 21100 Varese, Italy
3 INAF - Osservatorio Astronomico di Palermo, Piazza del Parlamento 1, 90134 Palermo, Italy
4 Infrared Processing and Analysis Center, California Institute of Technology, Pasadena, CA 91125, USA
5 IUSS Istituto Universitario di Studi Superiori, piazza della Vittoria 15, 27100 Pavia, Italy
6 INFN Istituto Nazionale di Fisica Nucleare, Sezione di Pavia, via A. Bassi 6, 27100 Pavia, Italy
7 W. W. Hansen Experimental Physics Laboratory, Kavli Institute for Particle Astrophysics and Cosmology, Department of Physics and SLAC National Accelerator Laboratory, Stanford University, Stanford, CA 94305, USA
8 Smithsonian Astrophysical Observatory (SAO) - Harvard Center for Astrophysics, Cambridge MA, USA
9 DIFPA - Dipartimento di Scienze Fisiche e Astronomiche, Universit degli Studi di Palermo, Piazza del Parlamento 1, 90134 Palermo, Italy
10 IMATI, Istituto di Matematica Applicata e Tecnologie Informatiche “Enrico Magenes”, Via dei Marini 6, 16149 Genova, Italy
11 Max-Planck-Institut für extraterrestrische Physik, Giessenbachstrasse, 85748 Garching, Germany
12 Department of Physics and Astronomy, University of Leicester, Leicester LE1 7RH, UK
13 Dr. Karl-Remeis Sternwarte and ECAP, Universität Erlangen-Nürnberg, Sternwartstr. 7, 96049 Bamberg, Germany

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ABSTRACT

X-ray emission from Young Stellar Objects (YSOs) is a key ingredient in understanding star formation. For the early, protostellar (Class I) phase, a very limited (and controversial) quantity of X-ray results is available to date. Within the EXTraS (Exploring the X-ray Transient and variable Sky) project, we have discovered transient X-ray emission from a source whose counterpart is ISO-Oph 85, a strongly embedded YSO in the ρ Ophiuchi star-forming region. We extract an X-ray light curve for the flaring state, and determine the spectral parameters for the flare from XMM-Newton/EPIC data with a method based upon quantile analysis. We combine photometry from infrared to millimeter wavelengths from the literature with a set of precomputed models. The X-ray flare of ISO-Oph 85 lasted ~ 2500s and is consistent with a highly-absorbed one-component thermal model (N_H = 1.0^{+1.2}_{-0.5} \times 10^{22} \text{ cm}^{-2} and kT = 1.15^{+2.35}_{-0.62} \text{ keV}). The X-ray luminosity during the flare is \log L_X [\text{erg/s}] = 31.1^{+2.3}_{-1.2}; during quiescence we set an upper limit of \log L_X [\text{erg/s}] < 29.5. We do not detect other flares from this source. The submillimeter fluxes suggest that the object is a Class I protostar. We caution, however, that the offset between the Herschel and optical/infrared position is larger than that for other YSOs in the region, leaving some doubt on this association.

To the best of our knowledge, this is the first X-ray flare from a YSO that has been recognised as a candidate Class I protostar via the analysis of its complete SED, including the submm bands that are crucial for detecting the protostellar envelope. This work shows how the analysis of the whole SED is fundamental to the classification of YSOs, and how the X-ray source detection techniques we have developed can open a new era in time-resolved analysis of the X-ray emission from stars.

Key words. stars: protostars, activity, coronae, flares; X-rays

1. Introduction

X-ray emission that largely arises from a stellar dynamo is a prime characteristic and well-studied phenomenon of pre-main sequence stars, both with and without accretion disks (Class II and Class III Young Stellar Objects (YSOs)). No standard dynamos are predicted for the earliest protostellar evolutionary stages of IR Class 0 and I. Yet X-ray studies of young star clusters have repeatedly come up with the detection of a small fraction of Class I objects (e.g., Prisinzano et al. 2008).

1 We adopted an infrared (IR) classification scheme for young stellar objects devised by Lada (1987) on the basis of the shape of their spectral energy distribution (SED).
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adaptive-binning technique segments the observation in time intervals (blocks) in which the count rate is perceptibly constant, i.e., does not show statistically significant variations. Our modified version (mBB in the following) is described in Vianello et al. (in preparation), and can account for highly-variable background such as that found during proton flares in XMM-Newton data. In short, for each observation we divide the field of view into partially-overlapping 30’ x 30’ regions and we run mBB on each of them. Regions with no signal return only one block, which covers the whole observation, while regions containing candidate transients, return three or more blocks. We are assuming here that the transients we are looking for are much shorter than the duration of the observation. Among all candidates found by mBB we consider as real astrophysical sources only those excrescences that have a spatial distribution consistent with the point spread function (PSF) of a point source. False positives can also be detected by mBB because of particle events, bright pixels, and other instrument-related effects. This is verified by running the standard source-detection algorithm on the candidates provided by mBB.

3. X-ray detection of ISO-Oph 85

One of the test fields for the transient source-detection algorithm developed within EXTraS was the ~138 ks long XMM-Newton observation number 0305540701, part of the Deep Rho Ophiuchi X-ray observation (DROXO), a 500 ks long XMM-Newton observation of core F in ρ Ophi (Sciortino et al. 2006). The transient X-ray emission from a point source at a position consistent with ISO-Oph 85 was discovered in the data from the PN EPIC instrument, both using the pipeline with fixed time bins (bin time of 3000 s) and using bayesian blocks analysis (in a time-interval of ~ 2500 s duration) in the 0.2 – 10.0 keV energy band. Using the pipeline-produced reference source list for the full observation without any soft proton filtering, ISO-Oph 85 is detected as a transient candidate, i.e., our pipeline does not detect it in the time-averaged image.

To establish the duration of the flare exactly we run the XMM-Newton SAS edetect_chain source detection routine on the PN events that were filtered for different time slices (10000 s, 1000 s, 500 s, and 100 s) and in different energy bands (0.3 – 2.0 keV, 2.0 – 12.0 keV, 0.3 – 12.0 keV). We start with the longest interval (10000 s) and then proceed to successively shorter intervals when, in the longer one, a detection is present at a position consistent with that of the transient source. The transient duration is ~ 2200 s, during which the source is detected with a significance > 5 σ in the broad band 0.3 – 12.0 keV. The distance between the X-ray source position and the HST/NICMOS position of ISO-Oph 85, which we will use as a reference position throughout this paper, is 2.2’.

Following Severgnini et al. (2003), we extract the number of detected X-ray sources with USNO-B1 counterparts and calculate the probability of a random association between the detected transient and ISO-Oph 85 with $P = 1 - e^{-(\sigma/\mu)^2}$, where $r$ is the X-ray source position uncertainty and $\mu \approx 10^{-4} \text{src/arcsec}^2$, the numerical density of X-ray sources. The chance probability is < 0.6%, suggesting that the identified transient X-ray source is associated with ISO-Oph 85.

The available XMM-Newton observations of the ρ Ophiuchi core F are all DROXO observations (0305540501, 0305540601, 0305540701, 0305540901, 0305541001, and 0305541101) plus a previous 34 ks-long observation 011120201 (Vuong et al. 2003). Observation 0305541001 was excluded from spectral analysis because of the very high soft proton contamination. Adding up all the available observations, we have a grand total of 209.1 ks of observation (Good Time Intervals, GTI, free from soft proton background, obtained using the bkgrate SAS tool). We perform a search for other transients from ISO-Oph 85 with the automated pipeline and visually inspect the images but no other flares were detected. We perform an analysis of the X-ray emission, extracting the energy spectrum (for the flare) and the light curve (for the whole GTIs of the observation 0305540501, in which the flare was detected, see Fig. 3).

In all DROXO observations the source position falls in a CCD gap for both MOS1 and MOS2 instruments, and so we consider PN camera data. For each observation, the background is extracted for the flare analysis from a circular source-free region on the same CCD as the source. During the flare, we observe a net source count rate of $1.762 \times 10^{-2} \pm 3.269 \times 10^{-3} \text{cts/s}$ in the band 0.3 – 12.0 keV. An X-ray luminosity upper limit is obtained for the quiescent regime of the source outside the HST/NICMOS position from Allen et al. 2002) is 2.2’ away.
flare, in which the source is not detected in X-rays within 3σ by edetect_chain. We consider all the GTIs of all the observations except the 2200 s of the flare as the quiescent time. For the quiescence, we obtain the background subtracted count rate upper limit at 3σ from the formula for the signal-to-noise ratio

\[
\frac{S}{N} = \frac{R_{\text{src}} \cdot T_{\text{exp}}}{\sqrt{R_{\text{bkg}} \cdot T_{\text{exp}} \cdot A_{\text{exp}} + R_{\text{src}} \cdot T_{\text{exp}}}},
\]

where the signal-to-noise ratio \(S/N\) is in σ and set \((S/N) = 3\), \(R_{\text{src}}\) is the source count rate upper limit, \(R_{\text{bkg}}\) is the background count rate, \(T_{\text{exp}}\) is the total exposure time minus the flaring time \(206.9\text{ks}\), and \(A\) is the area of the extraction region. The background count rate is obtained from a background extraction region of area \(~7\text{ times the source region on the same CCD of the source extraction region.}\) For the whole energy band \((0.3 - 12.0\text{ keV})\) we obtain a count rate upper limit of \(4.91 \cdot 10^{-4}\text{ cts/s}.\)

4. X-ray properties of ISO-Oph 85

4.1. Flare light curve

The X-ray light curve (Fig. 2) shows a clear count excess in two 1500 s-long adjacent time bins, corresponding to the detected flare. Because of the few counts \((39\text{ events from the whole 2200 s flaring time})\), it is not possible to infer the shape nor a decay time for the flare. We can only state that the decay time is less than \(3000\text{ s}^{}\) (twice the bin size). The low number of counts prohibits a standard spectral analysis. We observe a significant counts excess in the range \(2.0 - 6.0\text{ keV}\) with respect to a pre-flare and post-flare 20 ks interval (including mainly background counts), which suggests an impulsive heating episode, as is typical for a flare.

4.2. Flare spectral analysis

A technique for performing a spectral analysis on few-counts spectra, using quantile quantities, was developed by Hong et al. (2004) and used for the analysis of YSOs spectrally properties (e.g., Scelsi et al. 2007). We calculate the 25\%, 50\%, and 75\% quantiles of the counts of the flare observed from ISO-Oph 85. Then we derive the position of ISO-Oph 85 in the quantile space examined by Hong et al. (2004), defined by \(Q_{25}/Q_{75}\) vs \(Q_{50}/(1 - Q_{50})\).

A log \( T \) vs \( N_{\text{H}} \) theoretical grid, predicted by an absorbed one-component coronal thermal model (WABS*APEC) with fixed abundance \((Z = 0.3Z_\odot)\) from Anders & Grevesse (1989), and modeled via 100000 simulated spectra for a grid with log \( T \) from 6.5 to 8.00 and \( N_{\text{H}} \) from \(1 \cdot 10^{20}\text{ cm}^{-2}\) to \(N_{\text{H}} = 1 \cdot 10^{24}\text{ cm}^{-2}\), can be superimposed onto the phase space, thus giving the possibility to determine \(kT\) and \(N_{\text{H}}\) values for each point in the quantile space (Fig. 3). Following Scelsi et al. (2007), we compute this diagram for EPIC/PN data in the energy band \(0.5 - 7.3\text{ keV}\). We extract a spectrum of the flare and post-flare time \(\sim 3\text{ keV}\). We consider all the GTIs of all the observations except the \(12\text{ keV}\) flux during the flare \((3.75 \times 10^{-12}\text{ erg cm}^{-2}\text{s}^{-1})\), the X-ray luminosity \(\log L_x = \log (L_x/\text{erg s}^{-1}) = 31.6 \pm 1.2\) and the activity index \(\log (L_x/\text{erg s}^{-1}) = -2.33\). The bolometric luminosity \(\log L_{\text{bol}} = \log (L_x/\text{erg s}^{-1}) = 33.1 \pm 0.1\) is obtained with the Stefan-Boltzmann law using the effective temperature and stellar radius of the best-fit model.

4.3. X-ray luminosity during quiescence

From the upper limit to the quiescent count rate (as given in Sect. 5 times a conversion factor, we obtain an X-ray flux and luminosity upper limit. We calculate the conversion factor from the flux obtained with XSPEC for a WABS + APEC model, using for \(kT\) and \(N_{\text{H}}\) the values from the quantile analysis. Given the distance of the source \((120\) pc, Lombardi et al. 2008), we obtain the luminosity upper limit, that is \(\log L_x < 29.5\). We note that the formally most conservative upper limit, which we can derive from the uncertainties of \(N_{\text{H}}\) and \(kT\) obtained from the quantile diagram, amounts to \(\log L_x < 31.6\). By increasing the temper-

\[3\] XSPEC (X-Ray/Gamma-Ray Spectral Analysis Package) is a package for X-ray and Gamma-ray spectral analysis, provided by HEASARC NASA (Arnaud 1996).
5. Spectral energy distribution

The SED is key to understanding the evolutionary phase of a YSO. To this end, we collect all available photometric data for ISO-Oph85 from the literature and from data archives, we re-analyse Spitzer photometry, and we present as yet unpublished Herschel photometry of ISO-Oph85.

5.1. Multi-band photometry for ISO-Oph85

We cannot find any report of optical photometry for this object, presumably because of its large extinction. In some near-IR filters only the upper limits have been measured while mid-IR detections are available from various space missions (Spitzer, WISE, and ISO-CAM). WISE data in the W3 and W4 bands are listed in Table[1] but are not considered further because they carry a source contamination flag and, in fact, no source is seen on the images of W3 and W4 bands. The photometric point with the longest wavelength is the 1.3 mm flux measured with the IRAM 30 m telescope by Motte et al.[1998].

The Spitzer data are taken from the Cores to Disks Legacy Project, (c2d, PI Evans, pid 177) We perform aperture photometry in the Spitzer IRAC bands (3.6, 4.5, 5.6, and 8 μm) using the products available from the Spitzer Science Center (SSC) archive, and by adopting the recommended aperture[2] at all wavelengths. These, for a reference pixel size of 1.2 ″, correspond to 12 ″ (source aperture) and to 14.4 ″ and 24 ″ (sky apertures). This way we obtain flux densities that agree within 5 % with the values provided by the c2d collaboration (Evans et al. [2009]). We also perform aperture photometry in the MIPS 24 μm band using a 13 ″ source aperture and 20 ″ to 32 ″ sky aperture[3]. In this case, the computed flux is ∼ 40 % higher than the value found by Evans et al. [2009]. We investigate the source of such a discrepancy. To this end, we notice that the c2d collaboration carried out their photometric measurements using a point-source profile-fitting approach. Along these lines, we perform PSF-fitting of our source in the Mopex/Apex environment, where, as an input PSF, we use the MIPS 24 μm template that is publicly distributed by the SSC. After optimization of the Apex parameters, we obtain a flux-density value consistent with [Evans et al. [2009]], although with a poor reduced χ² (9.3). Accordingly, and for consistency with the IRAC measurements, we decide to adopt the higher value derived from our aperture photometry. Spitzer MIPS 70 μm data also exist, but the quality of these data is typically rather poor compared to data at the same wavelength from Herschel PACS 70 μm since they, as we ascertain, show flux non-linearities and artifacts. This is the result of the different types of detectors. We thus decide not to use them.

We also analyse as yet unpublished submillimeter photometry from the Herschel mission (Fig. 2). For the position of ISO-Oph 85, archival Herschel PACS and SPIRE parallel mode observations at 70 μm, 160 μm, 250 μm, 350 μm, and 500 μm from the “Probing the origin of the initial mass function: A wide-field Herschel photometric survey of nearby star-forming cloud complexes.” program (KPST_pandrel1) are available. The data have an angular resolution ranging from 6 ″ (at 70 μm) to 35 ″ (at 500 μm).

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[1]: IRAC Instrument Handbook
[2]: MIPS Instrument Handbook
[3]: http://irsa.ipac.caltech.edu/data/SPITZER/docs/dataanalysisstools/tools/mopex/
Fig. 5. Images from Spitzer IRAC 8 $\mu$m, MIPS 24 $\mu$m, Herschel PACS 70 $\mu$m, PACS 160 $\mu$m, and SPIRE 250 $\mu$m and 350 $\mu$m instruments with the HST/NICMOS position of ISO-Oph 85 and the position of the millimetric sources in the field of view (Motte et al. 1998). The instrument PSF is shown in the bottom right of each panel.

Given the difference in angular resolution between the NIR and mid-IR/submm data, it is important to make sure that the source that is visible in the lowest resolution band, i.e., Herschel SPIRE 500 $\mu$m, is indeed the same source that appears at shorter wavelengths. To this end, we adopt the location of the HST/NICMOS peak of emission as a reference. We then verify that the position of the peaks of emissions in each of the Herschel/PACS and SPIRE bands are within a FWHM from the position of the NICMOS peak, where the FWHM defines the PACS or SPIRE instrument resolution at a given wavelength. Fig. 4 shows an offset between the position of ISO-Oph 85 in HST/NICMOS and in Herschel SPIRE 500 $\mu$m, but it is well within the angular resolution of SPIRE 500 $\mu$m. Besides, there are no other millimetric sources that can be associated with the position of the emission peak in SPIRE 500 $\mu$m, and generate confusion in the association with ISO-Oph 85. We, therefore, associate the SPIRE emission peak with ISO-Oph85, but caution that the positional offset between submm and IR is larger than for most other YSOs in the region.

We reduce Herschel data via the Herschel reduction pipeline. We perform aperture photometry in the PACS and SPIRE bands. At IR and submm wavelengths, the background emis-
sion surrounding ISO-Oph 85 is highly structured and position-dependent (see Fig. [5]). For this reason, in each band we derive the source flux by taking the average of the values obtained by estimating the background from sky apertures that were placed at different locations in the source proximity. Using the median, the results do not change. Accordingly, the dispersion of the flux measurements around the mean value, combined with the intrinsic statistical errors, provide the flux errors. We use source and sky apertures of 12′′, 22′′, 40′′, 50′′, and 60′′ at 70 μm, 160 μm, 250 μm, 350 μm, and 500 μm. In the PACS bands, ISO-Oph 85 is barely visible above the background, therefore at 70 μm and 160 μm we are only able to place flux upper limits.

5.2. SED analysis

We model the SED of ISO-Oph 85 using the online SED fitter developed by [Robitaille et al. (2007)]. This algorithm compares the observed photometric data set with a precomputed grid of 200000 theoretical SEDs, which comprises 14 free parameters that characterize the star, the disk, and the envelope of the hypothetical YSO. As pointed out by [Robitaille et al. (2007)], because of the complexity of the χ² surface, this approach does not allow the true parameters of a YSO to be strictly determined, but, depending on the quality of the observed SED, it does allow meaningful constraints to be placed on a number of these parameters. Additional parameters are the interstellar extinction (A_V) and the distance (d). Throughout the fitting process both A_V and d are allowed to vary in a range that we set to A_V = 0 − 80 mag and d = 120 − 130 pc. These choices are motivated by the previous extinction estimate of [Comeron et al. (1993)] and the mean and spread of the distances cited in the literature for ρ Oph (see [Mamajek 2008], for a summary).

The filter list provided for Robitaille’s SED-fitting tool does not include the HST/NICMOS and the ISOCAM filters. Therefore, we have added these data points to the input of the SED fitter using the “monochromatic” option as an approximation. Given the uncertainties of the photometry related to zero-points and variability, the error introduced by neglecting the shape and width of the filter transmission is likely irrelevant. Following [Robitaille et al. (2007)], we impose a minimum of 10% flux error on all data points, and we base our assessment of the YSO parameters on the models with the smallest χ² values, i.e., the 37 models with χ² − χ²_best < 3 where χ²_best represents the best fit model (20 degrees of freedom). These are shown together with the observed SED in Fig. [5].

As can be seen in Fig. [5], a long-wavelength hump (representing emission from the envelope) is clearly visible. The hump is determined mainly by the Herschel data. If the hypothesis that the association with the Herschel peak is correct, this provides strong evidence for the protostellar nature of ISO-Oph 85. However, in this region of the SED the fit is not good. The uncertainties of the Herschel data are notoriously difficult to evaluate as a result of the strong spatial structure of the background emission at these wavelengths. The most evident feature in the distribution of the bestfit parameters is related to the masses of the disk (M_d) and the envelope (M_env). In Fig. [7] we compare the disk and envelope masses for the 37 best-fit models to those of the 10000 best fits. This shows that all best-fit models are among those from the available models with the highest envelope mass and accretion rate. The range of acceptable disk masses is large, while all bestfit models have high envelope mass. The range of best fit parameters is given in Table [2] where we also list the median and 25% and 75% quantiles for all fit parameters.

Using the definitions of [Robitaille et al. (2007)], based on disk mass and envelope accretion rate, we can assign an evolutionary ‘stage’ to the best-fit models. Stage 0/I represents objects with significant infalling envelopes and possible disks, and Stage II denotes objects with optically thick disks and possible remains of an envelope. All best-fit models for the SED of ISO-Oph85 correspond to Stage 0/I, underpinning the early evolutionary stage of the object.

In Sect 6 we compare ISO-Oph 85 to other X-ray sources in ρ Oph for which we use the YSO classes given by [Evans et al. 2009].
(2009) that are based on the slope of their SEDs ($\alpha_{\text{SED}}$) from $2-24\,\mu\text{m}$. For ISO-Oph 85 (Evans et al. 2009) determined $\alpha_{\text{SED}} = -0.29$ using 2MASS and Spitzer IRAC and MIPS 1 data. In our SED, we include addition primary photometry from HST, WISE, and ISO. The SED slope we find from a least-squares fit to the data given in Table I in the $2-24\,\mu\text{m}$ interval is $\alpha_{\text{SED}} = 0.10$. However, for consistency with the classification of the other DROXO sources, we also use the SED classification from Evans et al. (2009) for ISO-Oph 85. According to these results, ISO-Oph 85 is considered a "flat spectrum" source. We note, however, that the spectral index of ISO-Oph 85 is dominated by the low $K$-band flux and would be much steeper if the $K$-band were removed.

To summarize, our analysis of the SED of ISO-Oph 85 establishes this object as a bona fide Class I protostar. The Herschel photometry gives credibility to this object being a Class I protostar. A slight doubt remains with this classification because of the offset between the optical/IR and submm position of the emission peaks. Given the large uncertainties in the Herschel fluxes, we do not lend too much weight to the values for the disk and envelope parameters derived from the SED fits. The stellar parameters are likely robust against the uncertainties in the submm fluxes but subject to uncertainties from the extinction.

6. Discussion and conclusions

The observation of a flare from ISO-Oph 85 is of twofold interest. Firstly, it provides a first validation of the discovery and science potential of the EXTras project. Secondly, it gives insight into the physics, structure, and evolution of the YSOs. We showed that the analysis of the whole SED is fundamental for recognizing the evolutionary stage of YSOs, while the identification of the YSO class without submm data in the SED can lead to erroneous classification. This work also shows the possibility to perform a refined time-resolved analysis of the X-ray emission down to timescales that were previously inaccessible, and how such an analysis is fundamental for the understanding of the properties of the X-ray emission from YSOs. The object ISO-Oph 85 was detected in millimetric wavelength by Motte et al. (1998). Such long wavelength emissions can be a sign of protostellar nature, so the X-ray flaring activity from ISO-Oph 85 is particularly interesting, since X-ray flaring activity has rarely been observed in protostars. However, the wide gap in the SED between mid-IR (ISO/ISOCAM, Spitzer) data and the 1.3 mm detection leaves room for considering ISO-Oph 85 as a disk-bearing, envelope-free object, i.e., Class II source, as well. Our addition of Herschel submm photometry has been fundamental to removing this ambiguity. This makes the protostellar classification of ISO-Oph 85 reliable, compared to other published X-ray detected objects with presumed Class I status, which have been classified using Spitzer data. As a note of caution, we point out that there is a small offset between the HST/NICMOS position of ISO-Oph 85 and the position of the emission peak in Herschel, even if it is clearly within the Herschel positional errors. Even if we consider this scenario as quite unlikely, we cannot exclude that the emission observed in Herschel might be associated with a starless core and not with ISO-Oph 85. In this case, the millimeter identification of ISO-Oph 85 by Motte et al. (1998) would also likely be erroneous.

Another important aspect is that the X-ray emission from ISO-Oph 85 was detected only as a result of our systematic time-resolved search for transient emission. Pilitteri et al. (2010) do not detect it in the same data set, based on time-averaged analysis, which highlights the discovery space inherent in time-resolved source detection.

We calculate rough estimates for $kT$ and $N_H$ from the analysis of energy quantiles: $kT = 1.15^{+2.35}_{-0.65}\,\text{keV}$ and $N_H = 1.0^{+3.2}_{-0.5}\cdot10^{23}\,\text{cm}^{-2}$. At its lower end, the range of $N_H$ comprises the

Table 2. SED best-fit parameters. Errors represent 25% and 75% quantiles for the 37 statistically acceptable models as defined in Sect. 5 ($A_{V,cs}$ = total extinction, $A_{V,cs}$ = circumstellar extinction, inside the envelope cavity)

| Parameter          | Allbestfit |
|--------------------|------------|
| $N_{\text{H}}$     | 37         |
| $A_{V,\text{fit}}$ | 129.12     |
| $A_{V, \text{cs}}$ | 45.32      |
| $M_d \times 10^4$  | $M_\odot$  |
| $M_e$              | 0.7        |
| $M_e [M_\odot$ / yr] | 8.64      |
| $R_{\text{in}}$    | 690        |
| $R_{\text{out}}$   | 60.93      |
| $M_{\text{env}}$   | 0.123      |
| $M_{\text{env}} [M_\odot$ / yr] | 4.91 $^-4$ 76       |
| $R_{\text{env,in}}$| 1427.84    |
| $R_{\text{env,out}}$| 15151764 |
| $T_{\text{eff}}$   | 29602.856  |
| $R_e$              | 2.323      |
| $M_e$              | 0.145      |
| $R_e [R_\odot]$    | 129.12     |
| $A_{V,\text{fit}}$ | 129.12     |

Fig. 7. Distribution of model parameters for the 37 best-fit models (black histograms) and for the 10000 best-fitting models (grey histograms). The distributions are normalized to their peaks. From left to right: disk mass, envelope mass, envelope accretion rate.
value we derive from the optical extinction $A_V = 45.0^{+1.2}_{-1.0}$ that results from the SED fit. However, the gas-to-dust extinction law in star-forming regions is notoriously uncertain (Vuong et al. 2003). Using the above-mentioned spectral properties, we derive an X-ray luminosity of $L_X = 31.1^{+2.5}_{-1.8}$ erg/s for the flare of ISO-Oph85. The upper limit presented in the previous stage of ISO-Oph85 is $L_X < 29.5$, as derived using the $N_H$ and $kT$ value measured in the quillate diagram. The spectral properties of the X-ray emitting plasma of ISO-Oph85 are poorly constrained owing to low photon statistics. By making a comparison of the obtained temperature and absorption with other YSOs in DROXO, as detected by Pillitteri et al. (2010), we see that the flare emission from ISO-Oph85 is located in the medium-temperature and high-absorption tail of the distribution. In particular, its position is closer to the clustering region of the Class I and flat spectrum sources than to the bulk of the Class II and Class III sources. We also note that Class I sources cluster near the boundary of our grid, at very high temperatures and high absorptions (see Fig. 5), and the same is true for ‘flat’ sources. Class II and especially Class III sources instead tend to cluster in the lower half of the grid, which corresponds with lower hydrogen column densities, and with a wide range of temperature. Comparing these results with the distribution of YSOs that were observed inside the Taurus Molecular Cloud by Scelsi et al. (2007), we note that the barycenter of their distribution is located at a lower value of hydrogen column density with respect to the barycenter of the distribution in the $\rho$ Ophiciu cloud complex. This indicates a larger gas extinction in the $\rho$ Ophiciu cloud, which is consistent with the larger dust extinction observed in the IR.

According to Grosso et al. (1997), Ozawa et al. (2005), Imanishi et al. (2001), and Flaccomio et al. (2003), the X-ray activity of a YSO roughly tends to increase as it gets older, moving from an earlier YSO class to a later one, meaning that Class 0 and I protostars have lower X-ray activity than T Tauri stars (Class II and Class III). Among Class I protostars, X-ray emission has only been detected for a few objects, while the X-ray emission of Class 0 objects has yet to be confirmed. The fraction of X-ray detection of Class I protostars is generally smaller than for Class II and III. It is not clear if this is due to the high absorption, as DROXO X-ray luminosity functions suggest, or because of intrinsically lower $L_X$. A third possibility for the low X-ray detection rate of Class I objects, suggested by our result for ISO-Oph85, is strong variability paired with low quiescent X-ray flux.

By adopting the submm peak as representative of the envelope of ISO-Oph85, the flare observed on ISO-Oph85 confirms that protostars can exhibit strong X-ray activity. This behavior has already been noticed e.g., by Imanishi et al. (2001). However, most X-ray variability studies of protostars suffer from poor sensitivity and provide access only to coarse variability measures such as Kolmogorov-Smirnov (KS) statistics and poor time-sampling (Getman et al. 2007; Principe et al. 2014). The detection of a flare with $\approx 2$ decades amplitude is, therefore, notable. Since we observed only one flare in 209.1 ks of observation, we can state that X-ray flares of this amplitude or larger only occur in ISO-Oph85 every 2.5 d, roughly. This result is consistent with the flaring frequency observed in the Taurus Molecular Cloud (TMC) and in the Orion Nebula Cloud (ONC) by Stelzer et al. (2007). It is commonly thought that flares in embedded YSOs originate from coronal magnetic reconnection that is due to a stellar dynamo or to a magnetic reconnection between the field lines of the YSO itself, of the YSO and the disk, or of the disk itself. Since protostars are probably too young to have internal dynamo-like dynamics that are capable of producing intense magnetic reconnection from buoyant flux tubes (Hamaguchi et al. 2001) – as occurs in Sun-like stars – X-ray flares on protostars might be an indicator that the latter process dominates in X-ray emission. This could also mean that the stellar disk and possibly infalling envelopes have strong magnetic fields linked to that of the central forming protostar.

A systematic study of the X-ray flaring rate in $\rho$ Ophiciu will be carried out in a separate paper, and will allow us to compare the flaring frequency in the $\rho$ Ophiciu cloud complex with the results for TMC and ONC. A significant step forward in constraining the SED and understanding the YSO status could be made, for example, by using observations from the ALMA (Atacama Large Millimeter/submillimeter Array, Wootten & Thompson 2009).

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