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X-rays from Class 0/I Protostars

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Abstract. In the last decade, our interest moved significantly to the youngest stellar phase, "protostars". Evidence for infalls and outflows are implying violent star-forming activities close vicinity of the protostar itself. However, due to the very high extinction in optical and near-infrared band or even in soft X-ray band, we had no tool to access the star itself. In such situation, *Chandra* X-ray Observatory, with the high transparency in the hard X-ray band and the superior spatial resolution, are beginning to reveal X-ray emitting phenomena deep inside the protostellar cores. In this paper, the high energy activities in Class I and 0 sources detected with *Chandra* is reviewed.

1. Introduction

In 1980's, *Einstein* X-ray observatory discovered that T Tauri Stars (TTSs; ages $\sim 10^6$–10^7 yrs), or Class II and Class III infrared objects, are strong but variable X-ray emitters, with luminosities of $10^{28.5}$–10^{31} erg s^{-1}, about 100–10000 times larger than solar flares. The temperature ($\sim$1 keV) and plasma density ($n_e \sim 10^{11} cm^{-3}$) are comparable to those seen on the Sun. Thus, the X-ray emission mechanism has been thought to be a scaled-up version of Solar activity; i.e. magnetic activity on the stellar surface.

In contrast, Class I infrared objects (ages $\sim$ a few$\times 10^4$–10^5 yrs), which precede the Class II TTS phase and are considered to be in a late phase of protostellar evolution, are surrounded by circumstellar envelopes with A_V up to $\sim$ 40 mag or more. Therefore *soft* X-rays (< 2 keV) are absorbed and these deeply embedded sources are hard to be detected in the band.

The breakthrough was achieved in *hard* X-ray wavelength. Using the high transparency of the band, *hard* X-ray emissions from a few Class I sources in Rho Oph region were discovered with *ASCA* in 1994 (Koyama et al. 1994), and then the successive observations with *ASCA* and *ROSAT* further revealed that some other Class I protostars are X-ray emitters. However, not having enough spatial resolution nor sensitivity, previous X-ray satellites did not resolve the large percentage of protostars deep inside crowded cloud cores. With the superior spatial resolution and sensitivity of *Chandra*, we are now able to examine the protostars themselves, which have been impossible to gain access to in any other wavelengths. In the following sections, the most recent status on X-ray detections of Class I and 0 sources with *Chandra* is reviewed.

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2. Chandra observations of protostars

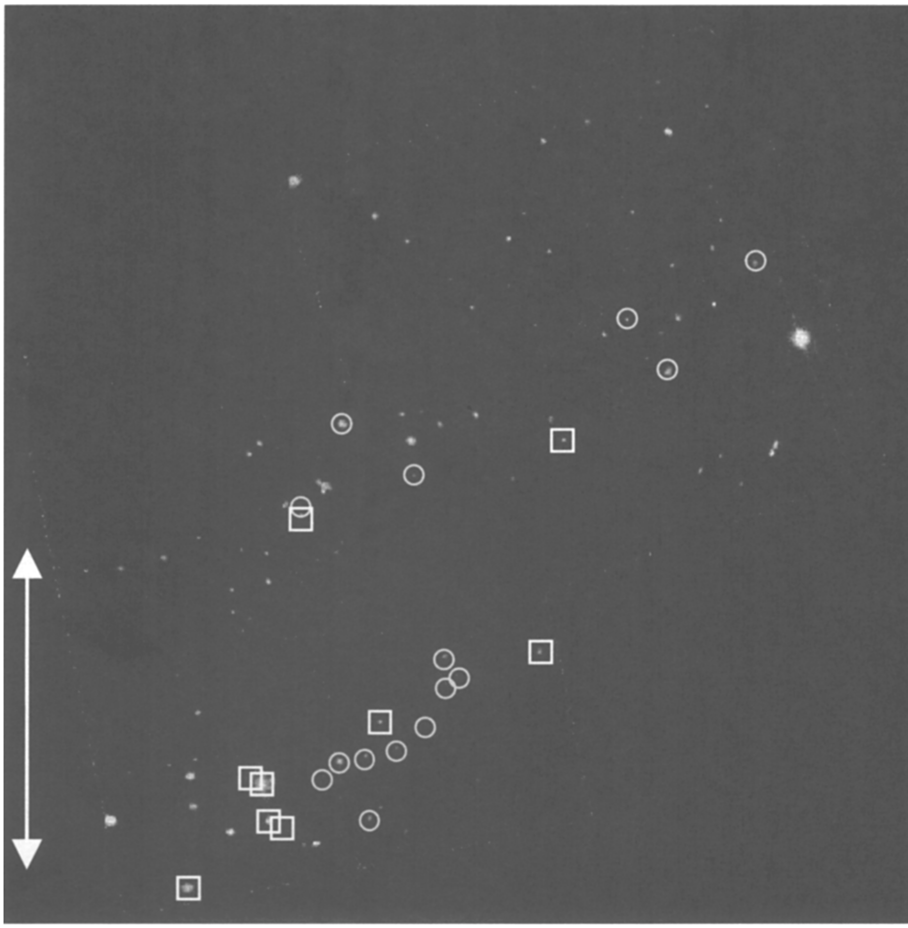

Figure 1. ACIS image of Rho Oph (Imanishi et al. 2003). Squares show the positions of bonafide Class I sources, and circles show those of Class I candidates.

Rho Oph: Imanishi, Koyama & Tsuboi (2001) executed long observation (100 ks) of the Rho Oph region with *Chandra*, where eight bonafide Class I protostars (Bontemps et al. 2001) and a dozen of Class I candidates reside in. They detected 70% of the bonafide Class I protostars as well as the same rate of the YSOs in the other phases (Class I candidates, Class II and Class III phases). It led them to the conclusion that virtually all Class I sources are X-ray emitters; the lack of X-rays from the other Class I protostars could be mostly due to the short and long time variabilities. Imanishi et al. (2003) further studied the same region adding the second observation (100 ks) dataset and detected flares from more than 60 % of the X-ray-detected Class I protostars. Class I–II sources tend to have a high temperature than Class III, which sometimes exceeds 5 keV. The

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higher temperature observed for Class I flares can be explained by a slightly higher magnetic field strength ($\sim$ 500 G) than for Class II–III sources (200–300 G). On the other hand, none of the 41 pre-stellar cores and one Class 0 protostar (VLA 1623) are detected in the *Chandra* observations.

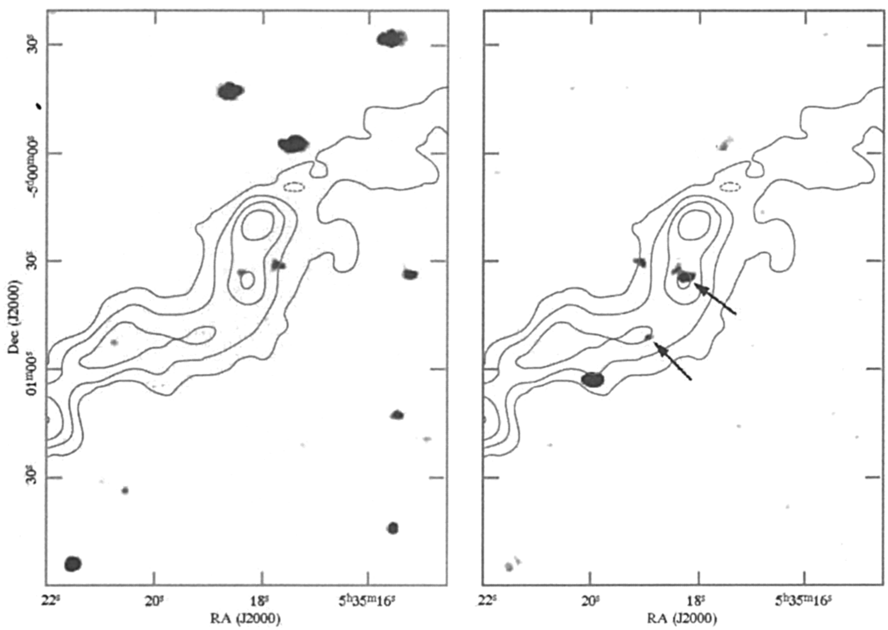

Figure 2. ACIS image of OMC 3 region (Tsuboi et al. 2001). Left: 0.5–3 keV, right: 3–6 keV. 1300 μm contour map (Chini et al. 1997) is overlaid. Two arrows indicate the positions of the Class 0 candidates MMS 2 and 3.

OMC 2/3: A chain of over a dozen protostars embedded in a thin dust filament in the Orion region was discovered with 1.3 mm and 3.6 cm observations (Chini et al. 1997, Reipurth et al. 1999). The protostar "islands" are elongated from the OMC 2 to the OMC 3 region. Most of the sources in OMC 3 region are identified as Class 0 objects (Chini et al. 1997, Lis et al. 1998).

Tsuboi et al. (2001) detected three hard X-ray sources (source 8, 8a, 8b) and one soft X-ray source (8c) within the error circle of MMS 2, and one hard X-ray source (10) within that of MMS 3. The hard X-ray sources 8 and 10 show absorption columns of (1–3) $\times 10^{23}$ H cm^{-2} which are one order of magnitudes higher than the typical value for Class I sources. The follow-up NIR (Tsujimoto et al. 2002) and MIR (Nielbock et al. 2003) observations revealed two Class I IR sources are located within the MMS 2 region. Tsujimoto et al. (2003) further detected centimeter emissions from both Class I sources using VLA. Since the position of the Chandra source 8 is significantly ($\sim$1–2″) offset from the Class I sources or the VLA sources, the origin of the hard X-ray sources is enigmatic. Tsujimoto et al. (2003) then proposed an interpretation that the hard X-ray emissions are shock-induced by protostellar jets, although they can

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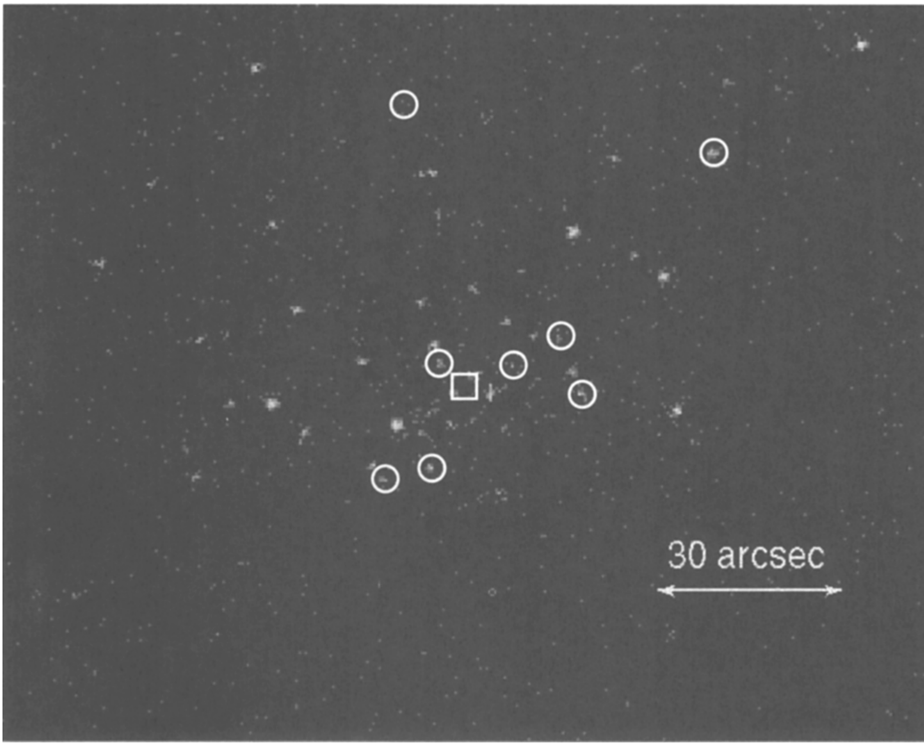

Figure 3. ACIS image of the central region of S106 (Tsuboi et al. 2003). Circles show the positions of X-ray-detected Class I sources. The square indicates the position of S106 FIR (no detection).

be originated by hidden Class 0 protostars, which are invisible by definition at infrared wavelength (Barsony 1994). The X-ray luminosities of the source 8 and 10 in the 0.5–10 keV band are estimated to be $\sim 10^{30}$ erg s^{-1} at a distance of 450 pc.

S106: The S106 region (d ~600 pc) is a site of clustering star formation. One Class 0 protostar S106 FIR (Richer et al. 1993) and about 140 of Class I protostars (Oasa et al. 2003) reside in the region. S106 FIR stands unique among all 40 known Class 0 sources in its lack of an extensive outflow (Hayashi et al. 1990, Richer et al. 1993, Furuya et al. 2000). Furuya et al. (1999, 2000) found a 10 AU scale jet through high angular resolution H_2O maser observations using the VLA and VLBI, then concluded that S106 FIR is the youngest protostar, observed before the formation of a well-developed molecular outflow.

Tsuboi et al. (2003) executed 50 ks observations of this region with *Chandra* and detected eight Class I protostars. They detected no X-ray emission from the Class 0 source S106 FIR (see figure 3).

The other star-forming regions: In the L1551 region in Taurus, two Class I protostars (L1551 IRS 5 and L1551 NE) are known to reside. Bally et al. (2003) detected the X-rays from the vicinities of both sources and confirmed the previous X-ray detection of IRS 5 with *XMM* (Favata et al. 2002). The derived

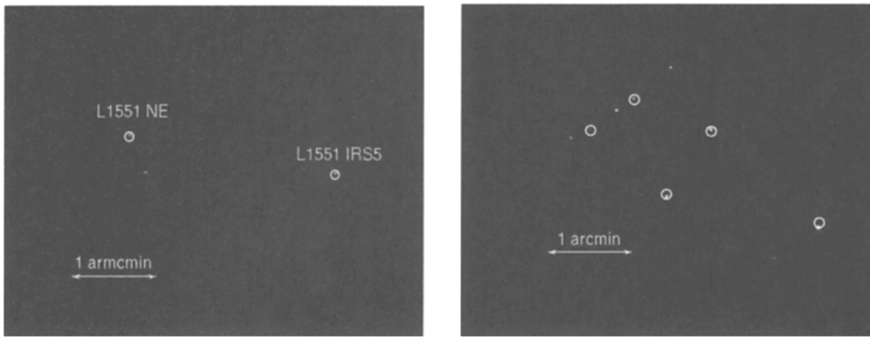

Figure 4. ACIS images of L1551 (left) and R CrA (right) with the positions of Class I sources indicated by circles.

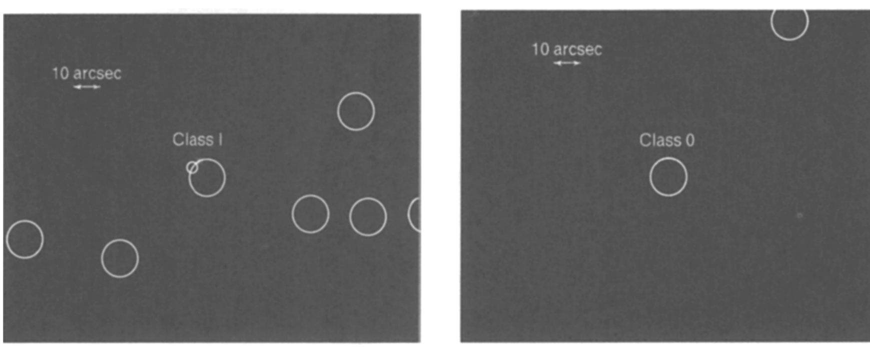

Figure 5. ACIS images of NGC 2068 focused on the Class I (left) and the Class 0 (right) positions. Large circles indicate the positions in submillimeter sources and the error radii (Motte et al. 2001), while the small circle in the left panel indicates those for the Class I source derived with 2MASS observation (Carpenter 2000).

column density of L1551 NE (log N_H ~22.0–23.0 cm^{-2}) is consistent with an origin from the protostar itself, however, that of L1551 IRS 5 (log N_H <22.3 cm^{-2}) and that derived with *XMM* (log $N_H \sim 22.1 \pm 0.1$ cm^{-2}) is much lower than the assumed visual extinction of roughly 150 mag (log $N_H \sim 23.5$ cm^{-2}). Together with the displacement ($0''.5$–$1''$) from the position of L1551 IRS 5 toward the blueshifted lobe of the protostellar outflow and slight extension of the X-rays, they concluded that a direct association of the X-rays with IRS 5 is unlikely. Then they argued the possibilities of jet origins and scattered X-ray origin.

In the Coronae Australis cloud (d ~130 pc), five sources are classified as Class I objects (IRS 1, 2, 5, 7, and 9). Koyama et al. (1996) detected all of them with *ASCA* with an X-ray flare from IRS 7. Neuhäuser and Preibisch (1997) detected three of them using the soft X-ray band with *ROSAT*. The *Chandra* observation with 20 ks exposure clearly confirmed the positional coincidence of X-rays with the five Class I protostars (Garmire et al. 2003).

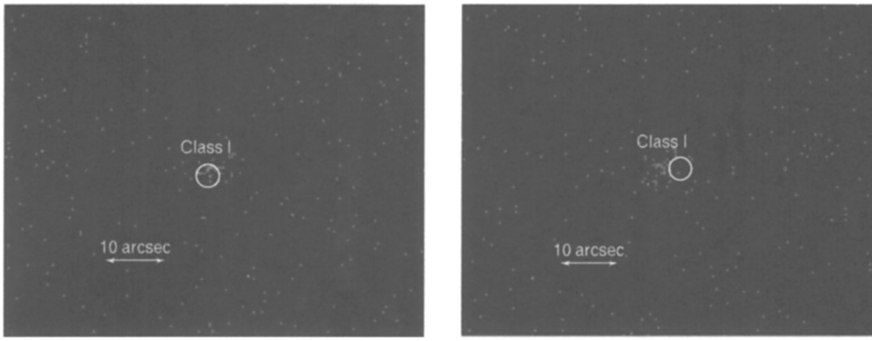

Figure 6. ACIS images of X-ray-detected Class I sources, 2MASS 34443.3+320131 (left) and L-51 (right) in IC 348 region.

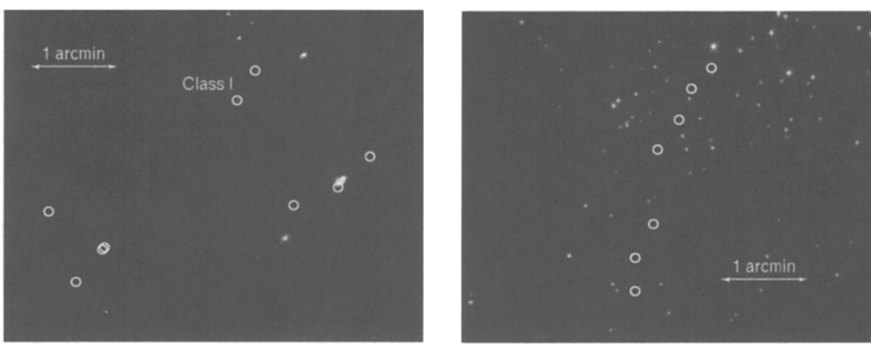

Figure 7. Left: ACIS image of NGC 1333 with positions of a Class I source and submillimeter sources including several Class 0 protostars (Sandell et al. 2001). Right: ACIS image of NGC 2024 and locations of FIR 1–7.

In the NGC 2068 region in Orion, one Class I and one Class 0 protostars reside, while 29 of pre-stellar cores exist (Motte et al. 2001). In the archival data of NGC 2068 (100 ks observation; PI Grosso), the Class I protostar is detected, while none of the Class 0 and pre-stellar cores are detected.

In the IC 348 region, only two Class I protostars/candidates are known. Preibisch et al. (2001) detected both of them. In the NGC 1333 region, one Class I protostar is detected by Getman et al. (2002), while none of the Class 0 sources and pre-stellar cores are detected. In NGC 2024, there are seven millimeter-bright cores (FIR 1–7) which may be protostellar. Skinner et al. (2003) reported that they did not detect the seven cores in X-ray wavelength, with the possible exception of faint emission (four photons) within 1.2″ of the position of the Class 0 candidate FIR 4. Pravdo et al. (2001) discovered X-rays from the jet HH 2. However, they detected no X-rays from the central protostar, the engine of the HH jets.

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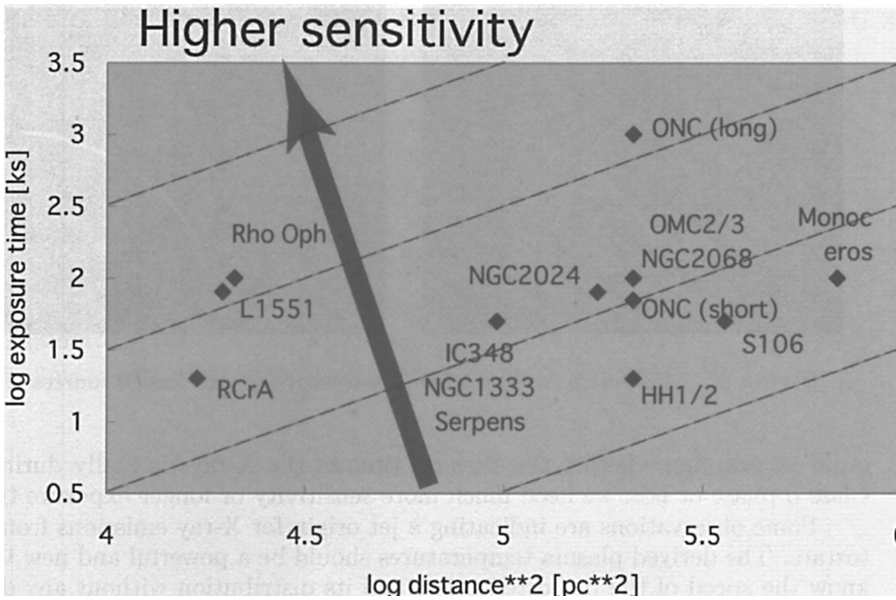

Figure 8. *Chandra* observations of star forming regions.

3. X-ray detections of Class I/0 protostars

The results in Rho Oph cloud are demonstrating that virtually all YSOs emit X-rays at least from the Class I phase and that X-ray turn-on occurs during the Class 0 phase. It is supported from the view that none of the over 50 pre-stellar cores are detected with *Chandra*, indicating that the protostar itself is essential for X-ray production. The frequent X-ray flaring indicates most of the Class I protostars are emitting X-rays magnetically.

In order to investigate the difference from region to region, we plotted star forming regions observed with *Chandra* in figure 8. The arrow indicates the direction of the sensitivity. In these observations, only Rho Oph, OMC 2/3, and S106 regions include more than 10 Class I sources. In figure 9 left, the detection rates of the Class I sources are plotted. Horizontal axis shows exposure time devided by squared distance which indicates the sensitivity. The detection rates in the above three regions are joined with a white curve. The gray curve indicates the estimated detection rate from the luminosity function of Class I sources in Rho Oph. The white and gray curves decay similarly as the sensitivity becomes smaller, and such decay is also seen in the other regions with poor Class I samples. This indicates that the difference in detection rates of Class I sources is roughly explained by only the sensitivity of the observations.

Figure 10 right is the same plot but for Class 0 protostars. Only OMC 2/3 has more than 10 Class 0 protostars/candidates. The X-ray detection of the two Class 0 candidates in OMC 3 are plotted, while non-detections in the other region are shown together. The large fraction of Class 0 sources could be not detected because of the column densities much higher than those of Class I sources. In

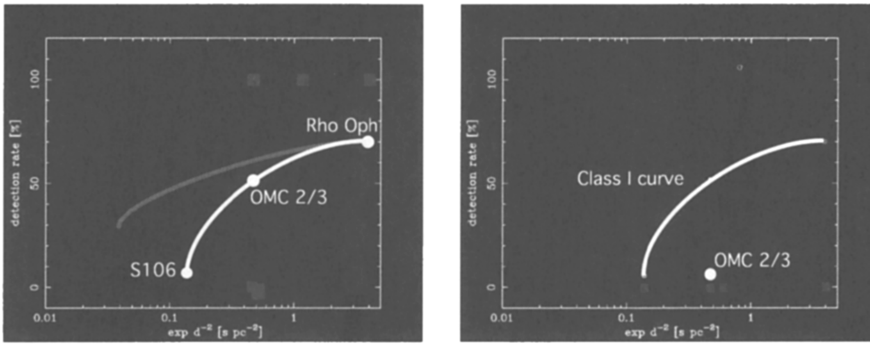

Figure 9. Detection rates of Class I sources (left) and Class 0 sources (right).

order to examine whether the turn-on time of the X-rays is really during the Class 0 phase or not, we need much more sensitivity or longer exposure time.

Some observations are indicating a jet origin for X-ray emissions from protostars. The derived plasma temperatures should be a powerful and new tool to know the speed of the protostellar jets and its distribution without any dependence on the inclination angle unlike proper motion or Doppler shift measurements.

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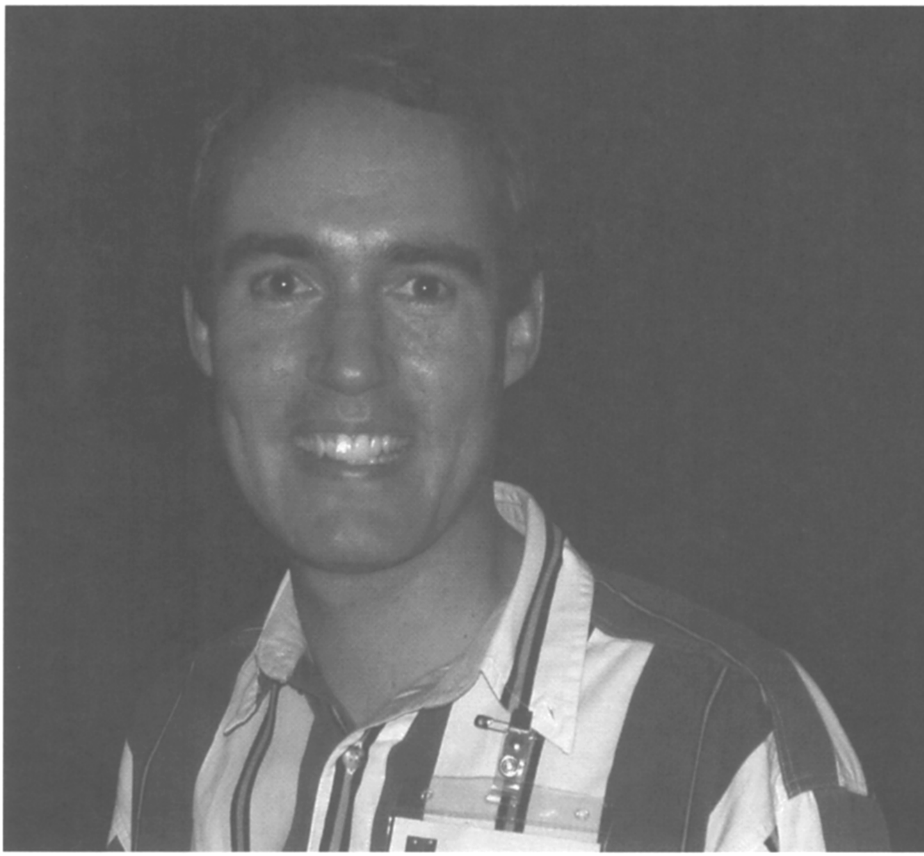

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