ASCA Observations of Embedded Sources in Dark Clouds

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ABSTRACT. This paper reports on the current status of hard X-rays from protostars detected with the ASCA satellite. From the center of the R Corona Australis (R Cr A) molecular cloud (called the Cornet cluster), we found hard X-ray point sources. One of the sources, probably the embedded far-infrared source R1, exhibited a powerful X-ray flare. These phenomena are similar to, but with a significantly higher temperature than, those seen in T Tauri stars. The flare spectrum is unusual, showing a broadened or double emission-line structure between 6.2 and 6.8 keV. The flux of this source decreased much with the second and third observations made one years after, instead another class I source became the brightest. Consequently, the Cornet cluster is found to be highly variable in the hard X-rays.

The ρ Ophiuchi dark cloud also harbors several X-ray emitting class I sources, two (EL29 and YLW15A) exhibited typical flares and another (WL6) showed a sinusoidal variation with no spectral change. The latter would be due to the rotation of the star.

Since X-rays are unexpected from current protostellar theories, these ASCA observations should have a significant impact on our understanding of star formation and the earliest phases of stellar evolution.

The NGC1333 and the Orion clouds II and III, also exhibited X-ray point sources visible only in the hard X-ray band, hence are highly possible to be embedded protostars. In addition to these clouds, a class I source is found in the Linds 1495E. Based on radio bipolar flow observations made on the ρ Oph dark cloud, we propose a unified picture of protostars.

1. Introduction

It is convenient to see the star evolution by the infra-red spectra. Stars of main sequence and late phase of T Tauri have no circumstellar gas, hence show black body radiations from the star surfaces. We call these the class III spectra. Classical T Tauris have accretion disks, and the spectra are the sum of the stellar surface and the accreting gas. These are the class II spectra. Protostars have class I spectra, which are dominated by infalling gas. Therefore radiations from the stellar surfaces are behind the stronger radiations from the circumstellar gas. Protostars or class I infrared sources are generally embedded deep in molecular clouds and/or dense circumstellar accreting gas. Therefore they are invisible with soft X-rays. We report hard X- ray results of these embedded protostars with the ASCA satellite.

2. The R Cr A cloud

Impressive ASCA results of a star forming region, the R Cr A dark cloud, are found in figures 1a and b in the paper of Koyama et al.(1996). In the soft X-ray band below 2 keV, the center of the cloud, which is shown by contour levels of the molecular gas, is dark; literally the dark cloud. Moving to the hard X-ray band, the center becomes bright. It shows complex X-ray structures. The position of class I objects are given by blue squares. We see a good correlation of the hard X-ray image and the position of the protostars. We therefore conclude that many of the protostars in the R Cr A cloud are X-ray emitters.

Figure 3 in Koyama et al.(1996) is an X-ray light curve of the center of the dark cloud, with a time span of a few days. A typical flare similar to T Tauri is found. The X-ray spectrum of the pre-flare phase is hard and is highly absorbed compared to T Tauris in the same cloud. Also we can see a clear emission line from the iron K-shell. In the flare phase, the spectrum becomes very strange, with two emission lines, separated about 0.5 keV (figure 4 in Koyama et al. 1996). If this separation is due to a Doppler effect, we need 10% of the light speed, suggesting presence of a sub-relativistic jet. Therefore this feature is particularly interesting, however I do not discuss detail now.

With follow-up observations of this cloud, we found a long term variability behavior of the hard X-rays. The X-ray images largely change from the first to the second observations made after two years. This means that virtually all the class Is in this cloud are highly variable. We also compared the X-ray spectra of the two observations, then found the spectra are also time variable.

3. The ρ Oph Dark Cloud

The next example is the ρ Oph dark cloud. Kamata et al (1997) shows the X-ray image of the central region of the cloud with the 2-energy bands (see figure 1c and 1d in Kamata et al. 1997). In the hard X-ray band, X-ray spots coincide to the class I objects are found. The brightest are protostars EL29 and WL6.

The X-ray light curve from the protostar EL29 showed a flare associated with spectral hardening. This is typical to T Tauris, but with a higher temperature.

The light curve of the other protostar WL6 was totally different from EL 29. It showed a sinusoidal modulation with essentially no spectral change. This is well demonstrated in figure 4 of Kamata et al.(1997). We suspect this is not a flare but would be due to a stellar rotation. If so, the rotation speed is as fast as about one day. In order to confirm this, follow-up observations were made after 3.5 years. Then we found WL6 (and also EL 29) became very faint and another class I source YLW15A exhibited intermittent flares. Before moving to other dark clouds, we list embedded class I sources in the R Cr A and the ρ Oph dark clouds in Table 1.

4. The NGC1333 Cloud

In the soft X-ray band (0.5 - 2 keV), we found 4 bright spots, which coincide to the HRI sources No's 10, 14, 15 and 19 (Preibisch, 1997). The brightest source is No. 10. We

Tab. 1 - Class I X-Ray Source List

Candidate	Note
R Cr A	
IRS2=TS13.1	variable
IRS5=TS2.4	"
IRS1=TS2.6=HH100IR=VSS15	"
IRS6=TS2.3	"
IRS7=R1	Flare, X-ray jets ?
ρ Oph	
EL29=YLW	Flare
WL6=YLW14	Rotation?
YLW15A=IRS43	Intermittent flares

Ref. Taylor and Storey (1984), Wilking et al. (1992), Wilking, Taylor and Storey (1986), Zinnecker and Preibisch (1984), Walter and Kuhi (1981) , Andre and Montmerle (1994) Elias (1978), Lada and Wilking (1984), Wilking , Lada and Young (1989).

also found a bright X-ray region with a peak between the positions of No's 17 and 18. Whether this spot is due to either No. 17 or 18 or both is uncertain at present. Even fainter sources are found at the positions of No's 5, 7, 16 and 20 and possibly at No. 11. In the hard X-ray band (4 - 10 keV), we clearly found X-ray peaks at the positions of No's 10, 15 and 19, of which No 15 is the brightest. At the position between No's 17 and 18, a hard X-ray spot was found as well as in the soft X-ray band.

New X-ray sources (no detection with the ROSAT HRI) were found mostly in the hard X-ray band (4 -10 keV): two bright spots at (3^h 29^m $16.^s$, 31^o $17'$ $52''$,) and (3^h 29^m 07^s, 31^o $17'$ $03''$), and unresolved X-rays near No. 15 sources. On the other hand, a spot at (3^h 29^m 25^s, 31^o $22'$ $26''$) was found both in the soft and the hard X-ray bands. In addition to these emission regions, lower surface brightness X- rays extending about 5' radius near (3^h 29^m 05^s, 31^o $15'$) were also found in the hard X-ray band. This would be an integrated emission of many faint X-ray sources, possibly embedded deep in the core of NGC1333.

5. Other Dark Clouds

A further example of hard X-rays from protostars is found in the dark cloud L1459E. The hard X-ray ASCA image of L1495 E shows X- rays at the position of a class I, IRAS 04154-2823 (Yamauchi, private communication). Also we found many hard X-ray sources in between the Orion Molecular cloud II and III (Yamauchi et al., 1996), which are probably objects in very young phases of star formations.

6. Summary of X-rays from Protostars

Several highlights of protostar X-rays, which should be noted are:

(1) We found quiescent X-rays , which have hard and largely absorbed spectra, with significant iron K-shell emissions.
(2) At least two protostars, R1 and EL29 exhibited flares , which are similar to a T Tauri, but with a higher temperature. The spectrum of R1 in a flare is very peculiar with two-lines structure.
(3) A sinusoidal flux modulation with no spectral change is found from WL6. It suggests that the star is rotating fast with a period of about 1 day.
(4) We also found long term flux and spectral variability's from many protostars.
(5) Some dark clouds harbor hard X-ray sources, which are not identified yet (NGC1333) or coincide to the positions of the molecular cores (OMC II and III).

7. Unified Picture of the Protostars

We certainly found X-rays from some protostars, but not for other protostars. An example of anti-evidence for X-rays from protostars is the densest region of the Chamaeleon II cloud; it has three class I sources, non of which shows X-ray emission even in the hard X-ray band of ASCA(Yamauchi et al. 1997). The most famous object of protostar, the bipolar object L1551-IRS5 also shows no X-ray (Carkner et al., 1996). The bipolar object in the ρ Oph dark cloud east, IRAS 16293-2422 shows no X-ray neither (Tsuboi, private communication) . So where does this difference come from?

To try to answer this question, we conducted radio observations on the X-ray emitting protostars. We discovered bipolar flows with small angle separation of the bipolar patterns (Sekimoto et al., 1997). This is in contrast to the well-known bipolar objects having lager separation patterns from which we found no X-ray. We propose one idea, a unified picture of protostars. Protostars have accreting circumstellar discs with a typical column larger than 10^{25} H/cm^2. and also have bipolar out flows with a smaller column of about 10^{23} H/cm^2. From the disk face-on viewing angle, we see absorbed X-rays and small separation angle bipolar patterns. Moving to the disk edge- on direction, we see no X-ray behind the extremely dense matter, but see largely separated bipolar flow patterns. The latters, of course, are known as famous bipolar objects.

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