HERBIG-HARO OBJECTS: A NEW CLASS OF X-RAY SOURCES?

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Abstract

X-ray emission from the shocks associated with jets from proto-stellar objects (Herbig-Haro objects) has recently been reported based on observations performed with both *XMM-Newton* (for HH 154) and *Chandra*(for HH 2). A search in ROSAT archive has shown that also the giant Herbig-Haro objects HH 355F and HH 311 are likely X-ray sources, although the limited statistics of the ROSAT data do not allow for their emission to be studied at any level of detail. For both HH 154 and HH 2 the emitted X-ray spectrum appears thermal – and thus likely to be originating in the shocks present in the Herbig-Haro outflows – with a best-fit X-ray temperature somewhat higher than expected on the basis of the measured shock velocity. We discuss the characteristics of the X-ray emission from the detected Herbig-Haro objects, their influence on the circumstellar environment and the prospects for future observations.

1. Introduction

Herbig-Haro objects are small, high-excitation nebulae commonly found in star-forming regions, in particular in the neighborhood of young stellar objects. They are normally associated with outflows originating from young stellar objects, and in particular with the shocks resulting from the jet hitting the circumstellar medium as well as with shocks internal to the jet itself. The shocks are sometimes described as "working surfaces", and UV and optical emission line spectra are often observed to originate from the shocks, indicative of high excitation temperatures, in the range from several 10^4 K to several 10^5 K and higher. For a recent general review of the properties of Herbig-Haro objects the reader is referred to Reipurth & Raga 1999.

Up and until the recently published *XMM-Newton* and *Chandra* observations discussed below, Herbig-Haro objects were not known as X-ray sources, even though their characteristics are such that X-ray emission could indeed be expected from them. In particular, no detection of X-ray sources associated with Herbig-Haro objects based on *Einstein* or ROSAT data was published.

In the present paper we discuss the recently published detections of X-ray emission from two Herbig-Haro objects, obtained with both *XMM-Newton* (for HH 154, Favata et al. 2002) and *Chandra* (for HH 2 Pravdo et al. 2001) observations, as well as significant evidence of X-ray emission from two other objects (HH 355F and HH 311) obtained by us analyzing ROSAT archival data.

2. XMM observations of HH 154

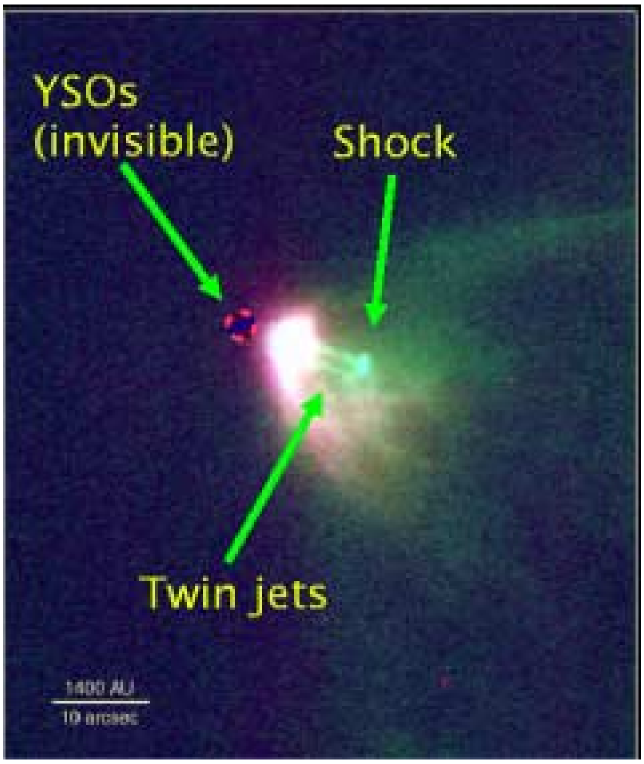

Figure 1. A Subaru telescope near-IR (J, K') image HH 154 (© 1999 National Astronomical Observatory of Japan). The twin jets and the jet's working surface are clearly visible.

HH 154 is a well studied binary outflow in the L1551 cloud. This cloud, at a distance $d \simeq 140$ pc, is one of the nearest sites of ongoing star formation. The HH 154 jet originates from the IRS5 source embedded in the L1551 cloud. L1551 IRS5 is a deeply embedded proto-stellar binary system (e.g. Rodriguez et al. 1998 and references therein), effectively invisible at optical wavelengths as it is hidden behind some $\simeq$ 150 mag of visual extinction

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(Stocke et al. 1988) which most likely originates in the circumstellar accretion disk. The two Class 0/1 stars have a total luminosity of $\simeq 30\ L_\odot$ and appear to be (jointly?) powering at least two observable outflows. A large (several arcmin) bipolar molecular outflow (actually the first discovered, Snell et al. 1980), and a much smaller (with a length of $\simeq$ 10 arcsec) denser two-component jet, which is powering the HH 154 shock. The twin jets are clearly visible in the near-IR image of Fig. 1. The jet and the molecular outflow have been shown to be likely causally unrelated, given that the jet has a momentum insufficient by several orders of magnitude to drive the molecular outflow (Fridlund & Liseau 1998). The jet moves at transverse velocity of 200–400 km s^{-1} (Fridlund & Liseau 1994) and appears to end in a shock against the ambient medium (a "working surface").

The L1551 region has been observed with *XMM-Newton* in a deep (50 ks) exposure, on Sep. 9 2000 (Favata et al. 2002). In the EPIC images (both in the pn and MOS cameras) a faint source (with a background-subtracted EPIC pn count rate of 8.4×10^{-4} cts s^{-1}) is present, positionally coincident with the HH 154 jet and shocks. The long exposure allows the collection of enough photons (ca. 50) to determine its general spectral characteristics. The EPIC pn image of the HH 154 region is shown in Fig. 2.

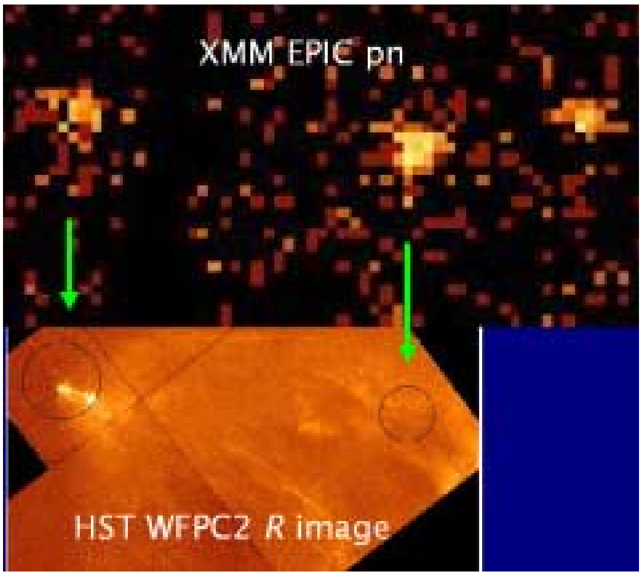

Figure 2. The top part shows the EPIC pn image of the HH 154 region, and below it is an HST R-band image. The leftmost X-ray source is positionally coincident with the HH 154 shock, while the second source (which has an absorbed hard power-law spectrum) is most likely a background, extra-galactic source (likely an AGN).

The spectrum of the X-ray source associated with HH 154 is shown in Fig. 3. It can be reasonably described with a moderately absorbed thermal spectrum: using a MEKAL model with an added interstellar absorption component in XSPEC gives a best-fit temperature $T_X = 4 \pm 2.5 \times 10^6$ K, with a moderate value of the best-fit absorption ($1.4 \pm 0.4 \times 10^{22}$ cm^{-2}), corresponding to an extinction of $A_V = 7.3 \pm 2.1$ mag, with a null hypothesis probability for the fit of 15%. Given the size of the XMM point-spread function (PSF) ($\simeq$ 14 arcsec for EPIC pn camera), significantly larger than the size of the jets (whose visible length is $\simeq$ 10 arcsec) it is not possible to locate the precise site of the X-ray emission within the jet structure.

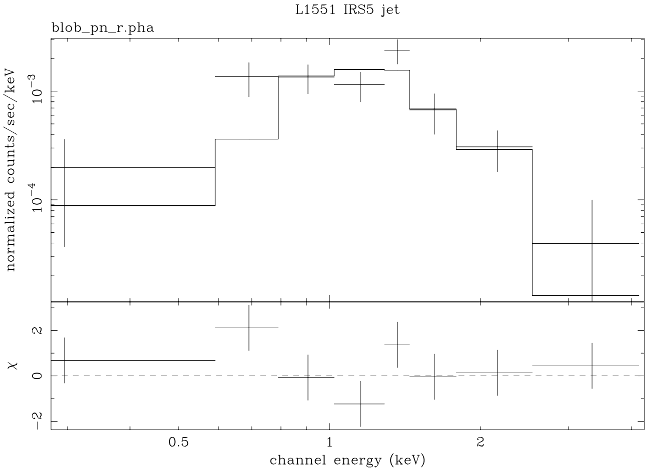

Figure 3. The observed, background-subtracted EPIC PN X-ray spectrum of the X-ray source associated with the L1551 IRS5 jet. The best-fit thermal ("MEKAL") spectrum is also shown.

Hubble Space Telescope (HST) observations show that a number of shocks are present along the extent of the HH 154 jet. The working surface (designated "knot D") where the jet impacts against the ambient medium is at $\simeq$ 10 arcsec from the presumed location of the source powering it (see Figs. 1 and 2 of Fridlund & Liseau 1998). The absorption column density toward knot D is measured to be $A_V = 4$–6 mag, increasing in the direction towards IRS5 along the jet. This absorbing column density is thus compatible with the absorbing column density measured for the EPIC pn X-ray source, making the association between the X-ray emission and the jet plausible. Since as mentioned above the IRS5 proto-stellar system is hidden behind a very thick layer of absorbing material ($A_V \gtrsim 150$ mag), it can be excluded that the X-ray photons – given the small absorbing column density and the lack of high-energy photons in the spectrum) – emanate from (or close to) the photosphere/chromosphere of the proto-stars powering the jet, making it very likely that the X-ray source is the result of thermal emission in the shocks.

As discussed in detail in Favata et al. (2002), the shock velocity is measured to be $\simeq$ 220 km s^{-1}, with a narrow shock interface, $\leq 1.0 \times 10^{14}$ cm. The immediate post-shock temperature can be estimated as in Raga (1989):

$$T_{\rm ps} \simeq \frac{2.9 \times 10^5 {\rm K}}{1+X} \times (\frac{v_{\rm shock}}{100\,{\rm km\,s^{-1}}})^2 \qquad (1)$$

where X is the hydrogen pre-ionization fraction and a number abundance of 0.9 (H) and 0.1 (He) has been assumed. With the nominal shock velocity the expected post-shock temperature for HH 154 is comprised in the interval $T_{\rm ps} \simeq 0.7$–1.3 MK, somewhat lower than than the observed X-ray temperature. The X-ray luminosity of the emission associated with the jets is $L_{\rm X} \simeq 3 \times 10^{29}$ erg s^{-1} (assuming a distance of 140 pc for the L1551 complex). This value is approximately an order of magnitude higher than the Hα luminosity of knot D, which is $\simeq 4 \times 10^{28}$ erg s^{-1} (Fridlund & Liseau 1994).

A characteristic size for the X-ray emitting region can be derived from the emission measure determined from the X-ray spectrum and the density determined from optical observations (see Favata et al. 2002). The emission measure is defined as $EM = \int n_e n_H dV \simeq 0.8\,n^2 V$, where n_e is the electron density, n_H the hydrogen density, and V is the volume of the emitting region (under the simplistic assumption of uniform density). Given that $EM = 1.1 \times 10^{52}$ cm^{-3} (from the thermal fit to the X-ray data), assuming a density $n_e \simeq 10^4$ cm^{-3} (see Favata et al. 2002), one derives a volume $V = 1.4 \times 10^{44}$ cm^3, which corresponds to a characteristic linear size $l \simeq V^{1/3} \simeq 5 \times 10^{14}$ cm. This scale size is comparable to the upper limit for the size of the shock interface derived from the HST observations, $\leq 1.0 \times 10^{14}$ cm, thus further supporting the identification of the shock interface as the seat of the X-ray emission.

3. *Chandra* OBSERVATION OF HH 2

Detection of X-ray emission from HH 2 in Orion ($d = 460$) was recently reported by Pravdo et al. (2001): in a 21 ks *Chandra* pointing of the Orion region they detected a weak soft X-ray source, positionally coincident with one of the brightest optical knots in HH 2. A total of 11 X-ray photons are associated with the source, all of them softer than $E = 2$ keV. Even though the limited source statistics does not allow for a detailed spectral study, assuming that the emission mechanism is thermal the energy distribution is compatible with a rather soft source, with $T \simeq 1.2$ MK. The X-ray luminosity of HH 2 is estimated by Pravdo et al. (2001) to be in the range 1–5×10^{29} erg s^{-1}, very similar to the value derived for HH 154 from the XMM observation.

The characteristics of HH 2 are in some respects rather similar to the ones of HH 154: in the model used to successfully predict the optical and UV emission from the object the shock velocity is estimated to be $v \simeq 160$ km s^{-1}, and the post-shock density is estimated $n \simeq 2000$ cm^{-3}, similar to the values quoted for HH 154. It is remarkable that the observed X-ray luminosity is also very similar to the one measured for HH 154. The high spatial resolution of *Chandra* allows for the size of the X-ray emitting region to be assessed. Pravdo et al. (2001) claim that the X-ray source associated with HH 2 is not point-like, but that it extends over some 2 arcsec. While the small number of photons does not allow an assessment of the source morphology, at the distance of the Orion cloud 2 arcsec correspond to $l \simeq 1.4 \times 10^{16}$ cm.

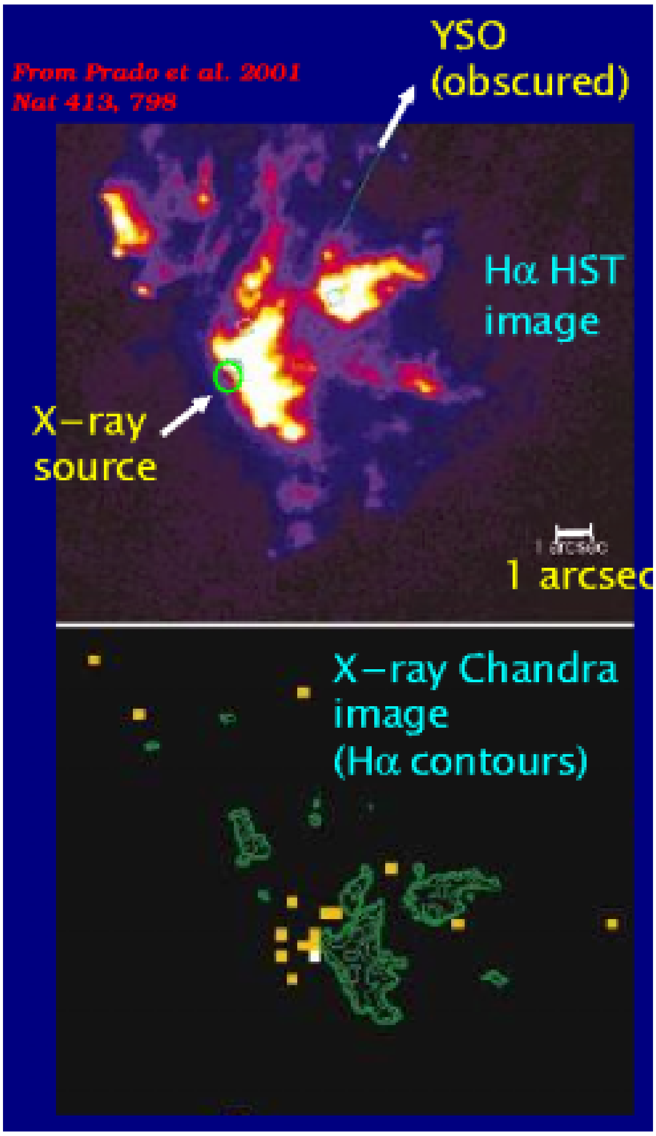

Figure 4. The Hα and Chandra *X-ray images of the HH 2 region, showing the location of the X-ray source together with the Hα contours (from Pravdo et al. 2001).*

Using Eq. 1, the post-shock temperature in HH 2 should be in the range $T_{\rm ps} = 0.4$–0.8 MK, depending on the pre-shock ionization fraction. As in the case of HH 154, the best-fit X-ray temperature derived from the *Chandra* spectrum is, at $T_{\rm e} \simeq 1.2$ MK, somewhat higher than the maximum expected post-shock temperature.

4. ROSAT OBSERVATIONS OF HH OBJECTS

To our best knowledge, no reports of X-ray emission from Herbig-Haro objects are found in the literature (prior to the *XMM-Newton* and *Chandra* observations discussed above). Nevertheless, stimulated by the *XMM-Newton* and *Chandra* results, we performed an initial search through the ROSAT archive for serendipitous detections of X-ray emission from Herbig-Haro objects. Although our search has not been complete (having been limited to a number of relatively well known Herbig-Haro objects) and should not therefore be considered as a "survey", we have found two cases in which strong evidence for X-ray emission is present.

4.1. HH 355F

The HH 355 jet is associated with T Tau, the prototypical pre-main sequence star which gave its name to the whole class. At least 7 distinct Herbig-Haro nebulosities are associated with T Tau, which is at a distance of $d \simeq 150$ pc, being located in the Tau star-forming region (as is HH 154). HH 355 is what is called a giant Herbig Haro flow, with a total projected extent of 1.55 pc, centered on T Tau itself (Reipurth et al. 1997a). The individual knot which appears to be associated with an X-ray source is H355 F, and is located at some 15 arcmin from T Tau (i.e. some 0.6 pc, a much larger distance from the parent star than in the case of e.g. HH 154). HH 355F appears to have a dynamical time scale of about 5000 yr and is the outermost knot of the jet, exactly aligned on the jet axis passing through the inner knots. It can be interpreted as the position where the jet breaks through the natal cloudlet surrounding T Tau and impinges on the ambient medium.

T Tau has been the target of a number of ROSAT PSPC observations, and – given the wide field of view of the PSPC – HH 355 falls in the field of view and was thus also serendipitously observed. The large distance from T Tau also implies that X-ray emission from the Herbig-Haro object can be detected even the in presence of strong X-ray emission from the parent star.

The detection of X-rays from HH 355F is – given the limited spatial resolution of the PSPC – however hampered by the presence of a nearby field dMe star (Gl 3275), located at just 1.5 arcmin from HH 355F itself. In fact, an X-ray source is detected in the ROSAT PSPC observations of T Tau, with a centroid located about midway between HH 355F and Gl 3275. If both the Herbig-Haro object and the dMe star are significant X-ray sources, at the resolution of the ROSAT PSPC they would indeed be expected to merge into a single, unresolved (albeit somewhat extended) source. Strong indication of HH 355F actually being a soft X-ray source comes from the shift in source position as a function of photon energy: the left panel of Fig. 5 shows the PSPC image accumulated in the hard band ($E > 0.4$ keV), while the right panel shows the PSPC image accumulated in the soft band ($E \leq 0.4$ keV): the centroid of the X-ray emission shifts, when going to the hard band from the dMe dwarf (which appears to have a harder spectrum than the Herbig-Haro object) toward HH 355F. Thus, even if the source is formally unresolved, the PSPC observation is strongly indicative of the presence of soft X-ray emission from the HH 355F shock.

The strong contamination from Gl 3275 does not allow for the characteristics of the X-ray emission from HH 355F to be studied at any level of detail. However, the dominance of the source in the PSPC soft band ($E \leq 0.4$ keV) implies that the X-ray source is both less absorbed and at an intrinsically lower temperature that the one associated with HH 154. For the soft emission to be dominating above the hard one in the PSPC data, the emitting plasma must have a temperature of $T \lesssim 1$ MK. Assuming this value for the temperature, and attributing half of the observed PSPC count rate from the soft source of Fig. 5 to HH 355F (i.e. ca. 0.05 PSPC cts/s), a lower limit to the X-ray luminosity associated with HH 355F in the 0.2–5.0 keV band (assuming a distance $d = 150$ pc and *no* absorbing column density) is $L_{\rm X} \gtrsim 5 \times 10^{29}$ erg s^{-1}, very similar to the X-ray luminosity of HH 154 and HH 2. If a substantial amount of absorbing column density is present (as it is indeed in HH 154) the intrinsic X-ray luminosity could be much higher: if the same absorbing column density as for HH 154 is assumed, the X-ray luminosity would be about two orders of magnitude higher. The very limited statistics of the ROSAT PSPC data do not allow for the spectral characteristics of the source – and thus for the actual X-ray luminosity – to be estimated.

4.2. HH 311

HH 311 is the shock at the end of the giant Herbig-Haro flow HH 111. HH 111 appears morphologically to be a textbook case of what a jet should look like with a well collimated sequence of knots (Reipurth et al. 1997a). This object attains a total length of 7.7 pc with well defined shocks at the end of the jet. These are themselves designated HH 113 and HH 311 and are separated by 57 arcmin. HH 311 is also associated with a major molecular outflow and shows thus the same kind of outflow activity as HH 154, albeit with much higher energies, masses and momentum, so that proportionally larger X-ray emission is likely to be associated with the jet.

HH 111 (and thus its components, including HH 311) is located in Orion, ($d \simeq 470$ pc). HST observations of HH 311 are reported by Reipurth et al. (1992) and by Reipurth et al. (1997b), who deduce large ($v \simeq 600$ km/s) velocities for the jet material, and a density of $n \simeq 10$ cm^{-3}, which ensure a shock temperature compatible with soft X-ray emission, and perhaps higher than for the other shocks discussed here, which have lower velocities. HH 311 falls serendipitously in a 25 ks ROSAT HRI observation; a faint source (ca. 10^{-3} HRI cts/s) positionally coinci-

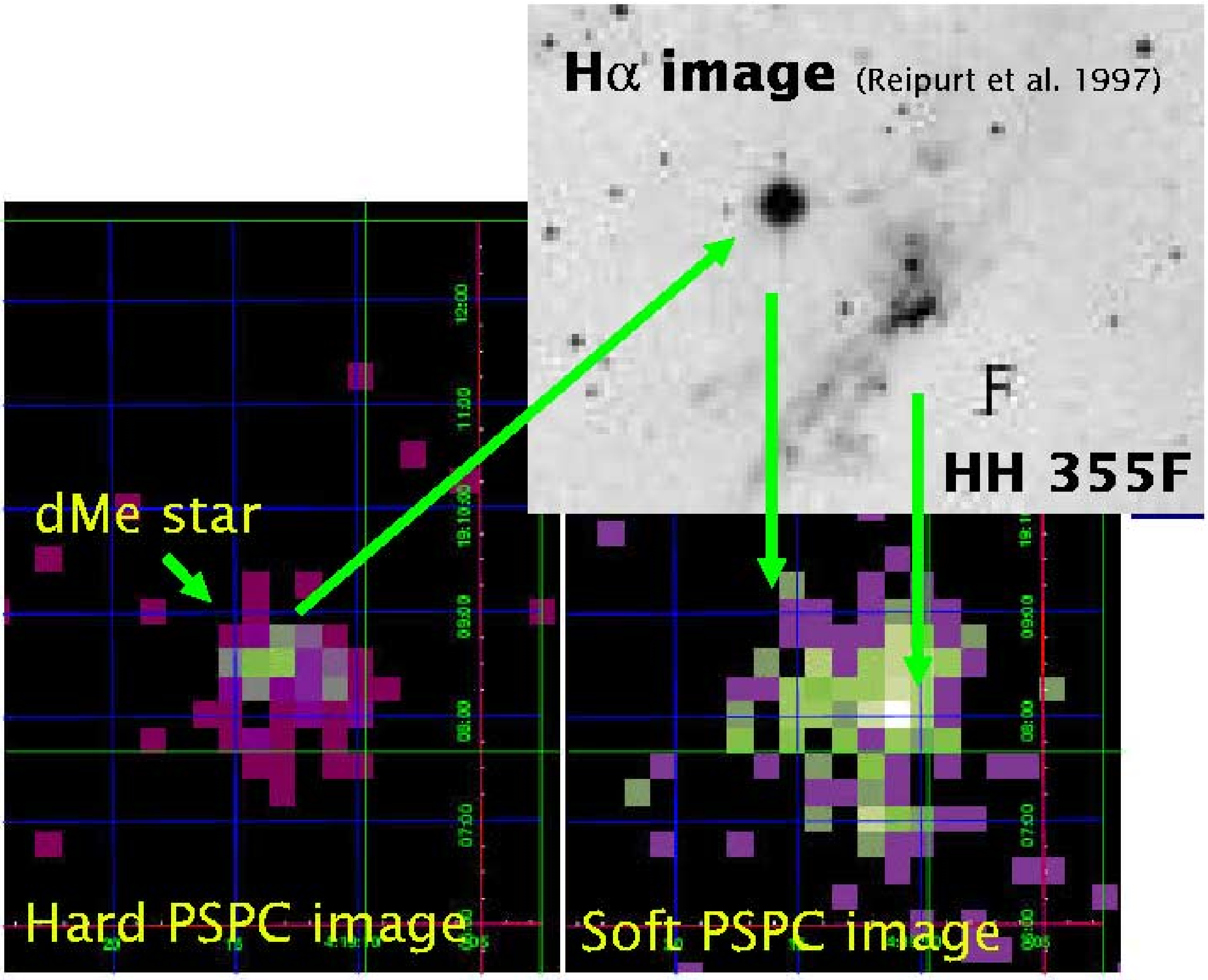

Figure 5. *The soft (left panel) and hard (right panel) PSPC image of the source associated with HH 355F and Gl 3275. The centroid of the X-ray source shifts when comparing the hard and soft bands, indicating that an additional soft source is present, not visible in the hard-band image (where only the nearby dMe star is visible). The centroid of the additional source is positionally coincident with HH 355F.*

dent with the HH 311 jet is present in the observation. Assuming that the X-ray temperature of HH 311 is comprised between the "cool" 1 MK assumed for HH 355F and the higher temperature observed for HH 154, the inferred lower limit to the X-ray luminosity in the 0.2–5.0 keV band (again for no intervening absorbing material), at a distance of $d = 470$ pc and for the observed HRI count rate, is $L_X \simeq 4\text{–}6 \times 10^{29}$ erg s^{-1}. As for HH 355F, if significant absorbing column density is present, the intrinsic X-ray luminosity could be up to two orders of magnitude higher. Once more, the lack of spectral resolution and very limited statistics of the HRI data does not allow for any assessment of the source's spectral characteristics.

5. Discussion

The identification of HH 154 and HH 2 with X-ray sources, on the basis respectively of their *XMM-Newton* and *Chandra* observations appears firm, given the very good positional coincidence, together with their thermal spectrum and the lack of temporal variability. For HH 154 the very high absorbing column density toward the parent protostar allows to rule out that its soft X-ray emission could be detected and thus contaminate the X-ray source associated with the Herbig-Haro object. Thus, it appears now firmly established that Herbig-Haro objects are a new class of astrophysical X-ray sources. Nevertheless, not all Herbig-Haro objects are X-ray sources (see e.g. HH 30 below). How common is it, remains to be established with more observations of a large number of objects.

Many Herbig-Haro objects will however not be good targets for X-ray observations: as the X-ray luminosity of Herbig-Haro objects is – on the basis of the limited evidence currently available – comparable or lower than the X-ray luminosity of the parent young stellar objects, and many Herbig-Haro objects are found very near the parent star, their X-ray emission – if present – may be hidden in the "glare" of the emission from the parent star. The peculiar situation of HH 154, with its parent star deeply hidden, has allowed for its detection without interference from the stellar X-ray emission. The high spatial resolution of *Chandra* may, in some cases, allow to resolve the stellar and shock-associated emission. Giant Herbig-Haro flows, with their large separation from the parent star, do not present this problem (allowing their detection even in the archival ROSAT data discussed above).

The Herbig-Haro objects for which evidence of their being X-ray sources is available show some similarity. In particular, the X-ray luminosity of the *XMM-Newton* and *Chandra* observed objects (HH 154 and HH 2) is, at a few times 10^{29} erg s^{-1}, very similar. In the case of the objects detected in the ROSAT archival PSPC and HRI observations (HH 355F and HH 311) the lower limit to their X-ray luminosity is very similar to the actual luminosity of HH 154 and HH 2. However, the presence of a significant amount of absorbing material would increase significantly the source X-ray luminosity: if they were to have the same amount of absorbing material as HH 154 their intrinsic X-ray luminosity would be around 10^{31} erg s^{-1}, comparable to the X-ray luminosity reached during large (proto-)stellar flares, so that they would be an important element in the energetics of the proto-stellar system.

For both the *XMM-Newton* and *Chandra*-observed Herbig-Haro objects the X-ray temperature is hotter than expected on the basis of the shock velocity measured in the optical and of the simple model of Raga (1989) (i.e. Eq. 1). For HH 2 (for which the discrepancy is noted by Pravdo et al. 2001) the expected post-shock temperature $T_{\rm ps} = 0.4$–0.8 MK (depending on the degree of pre-shock ionization) is to be compared with the best-fit temperature to the photon distribution $T_{\rm X} = 1.2$ MK (which in this case is however based on a fit to only 11 detected X-ray photons). For HH 154 the best-fit temperature from the *XMM-Newton* spectrum is $T_{\rm X} = 4$ MK, higher than the post-shock temperature $T_{\rm ps} = 0.7$–1.3 MK (again depending on the degree of pre-shock ionization). Pravdo et al. (2001) remark that the range of post-shock temperature could, in the case of HH 2, indicate that the actual X-ray temperature is lower. In the case of HH 154 the higher statistics of the *XMM-Newton* spectrum allows to exclude this with a reasonable degree of certainty, so that the discrepancy appears to be real. The discrepancy therefore implies that – if indeed the X-ray emission is the result of shock-heating at the jet's working surface – it could be the product of a localized higher-velocity shock. Given the quadratic dependence of the post-shock temperature on the shock velocity, a moderate increase in the shock velocity is sufficient to justify the observed X-ray temperatures. The range of shock velocities necessary to explain the observed 4 MK emission is for HH 154 (inverting Eq. 1), $v_{\rm s} = 370$–530 km s^{-1} (the higher value being for a fully ionized pre-shock jet, as found by Fridlund & Liseau (1998). Such velocities are a factor of two higher than observed in the jet. A similar reasoning for HH 2 leads to a range of velocity $v_{\rm s} = 200$–290 km s^{-1} again of order of a factor of two higher than observed.

Even though the evidence presented here shows that many Herbig-Haro objects are likely to be X-ray sources, it is also clear that not all Herbig-Haro objects are X-ray sources. Some protostellar outflows have no strong shocks associated with them (no "working surfaces"), and it is thus not to be expected that they would show X-ray emission. For example, another well studied Herbig-Haro object in the L1551 region (the same as HH 154) is HH 30, which also fell in the field of view of the *XMM-Newton* observation of HH 154. No X-ray source down to the sensitivity limit of the data set is visible, allowing to put a significant upper limit to the luminosity of an X-ray source associated with HH 30 of $L_{\rm X} \lesssim 3 \times 10^{28}$ erg s^{-1}, an order of magnitude fainter than the X-ray luminosity associated with the Herbig-Haro objects which do show X-ray emission. Indeed, the optical (HST) images of HH 30 do not show evidence for brightenings in the jet, so that the jet appears to dissipate without significant shocks being formed.

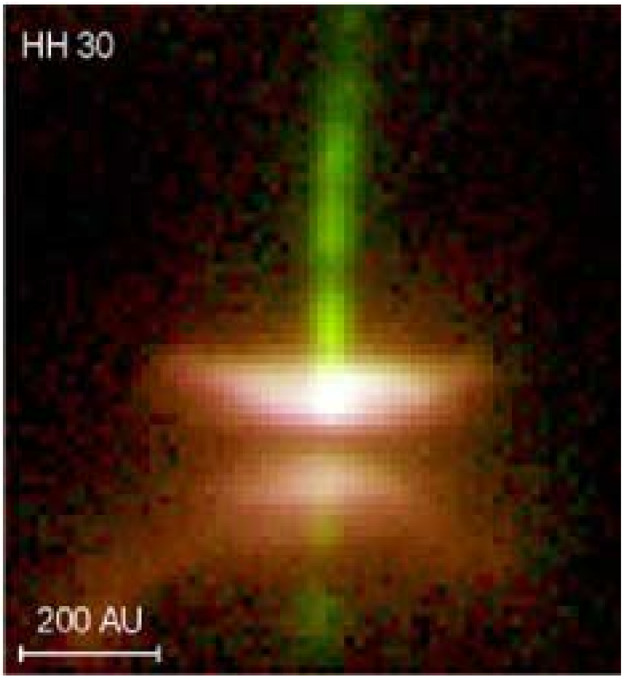

Figure 6. Optical HST picture of the HH 30 outflow in the L1551 region (from the HST www site).

In the cases in which the Herbig-Haro objects are indeed significant X-ray sources, however, they may likely influence the ionization state of the disk. Young stellar objects are likely to have significant X-ray coronal emission, often more luminous than the X-ray luminosity of the Herbig-Haro object shock, and in particular flares can reach peak X-ray luminosities of some 10^{31} erg s^{-1}. Given that the typical recombination time for disk and circumstellar material ($t \approx 30$ yr, Glassgold et al. 2000) is much longer than the typical flaring rate, flares are likely to be more important in determining the ionization state of the disk than the quiescent X-ray emission from young stars. However, the scale height of the stellar coronal emission above the stellar photosphere is small (e.g. Favata et al. 2001), so that the angle of incidence of the coronal X-rays for all but the very inner parts of the disk will be very small. As discussed in detail e.g. by Glassgold et al. (2000), this implies that even the powerful flaring X-ray emission may actually only ionize the surface layers of the disk, leaving the interior in a neutral state.

X-ray emission from Herbig-Haro objects will on the other hand impact the disk at near-normal incidence even in its outermost regions (see Fig. 7 for a schematic hypothetic representation of the geometry), so that its contribution to the ionization of the disk might be significant, even if the Herbig-Haro object X-ray luminosity is not dominant with respect to the stellar coronal X-ray luminosity. Detailed calculations will be needed to assess whether the incident X-rays generated at the shock front (which are subject to the absorption of the intervening material, which might be relevant at least for the softer photons, and which are generated at larger distances from the disk than the stellar coronal X-rays) will indeed be a potential significant source of ionization for the disk material.

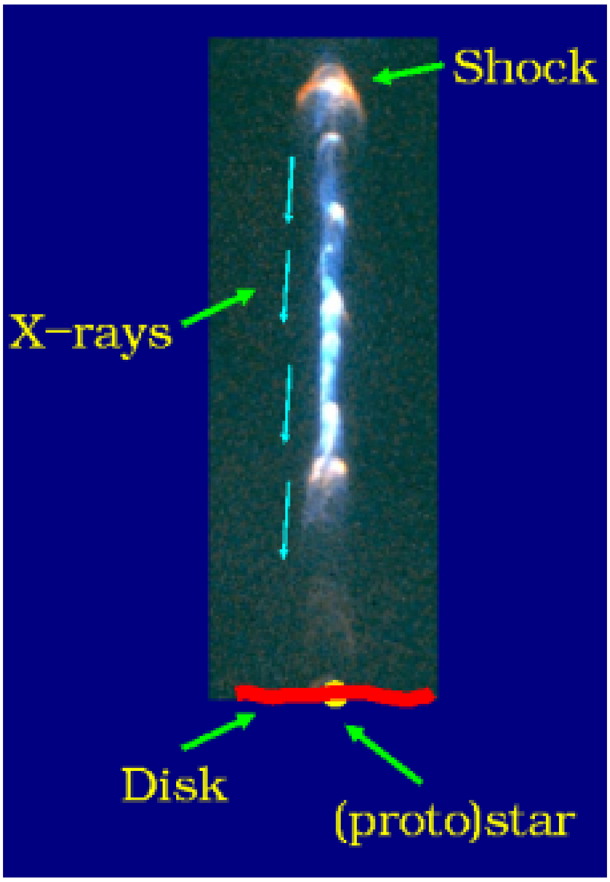

Figure 7. A schematic representation of the geometry with which X-ray emission from Herbig-Har shock at the end of a proto-stellar ouflow would illuminate the accretion disk. An HST visible image of HH 111 is used as hypothetic example – however no X-ray emission has been detected to date from the specific shock pictured here.

6. CONCLUSIONS

Thanks to the improved sensitivity offered by both *XMM-Newton* and *Chandra* “first” detections of the X-ray emission from Herbig-Haro objects have been recently reported, and the much improved throughput of both missions allows for the detected emission be studied in detail. An analysis of ROSAT serendipitous observations of giants Herbig-Haro objects shows that tantalizing evidence (not reported previously) for their being X-ray sources was already present there. The X-ray flux of these ROSAT-detected Herbig-Haro objects is such as to allow detailed spectral and morphological studies to be performed with *XMM-Newton* and *Chandra*, and we have indeed proposed their observation in the context of the Guest Observer's program of both observatories. One question which should be addressed with the high S/N spectra which could be obtained with *XMM-Newton* e.g. for HH 355F is whether the emitted spectrum is indeed thermal or whether – being formed in a shock – is being emitted by plasma in non-equilibrium ionization.

The optical and UV emission of Herbig-Haro objects is observed to vary on relatively short time scales (weeks and months, as well as longer time scales). Nothing is of course known up to now (for lack of data!) about the variability of their X-ray emission. A (near) simultaneous study of their X-ray and optical emission would allow to assess whether their X-ray emission is indeed as variable as the optical and UV emission, and correlation of the variability among the various spectral components would be a powerful diagnostic of the mechanisms and location of the X-ray emission.

The X-ray emission detected in Herbig-Haro objects appears to be at a somewhat higher temperature than predicted from the shock velocities observed in the optical. Whether this is due to the presence of small high-velocity knots not detected in optical observations or to some other mechanisms remains to be established. The energetics of the X-ray emission appears (at least in the case of HH 154) to be important in the total energy balance of the shock, with an X-ray luminosity approximately an order of magnitude higher than the Hα luminosity.

Stellar X-ray emission is thought to be an essential ingredient in the ionization of the disk and in its coupling to the stellar magnetic field. As the geometry of the shock X-ray emission is such that it will illuminate the accretion disk with near-normal incidence its influence on the ionization of the disk's outer regions might be important, and it should be assessed with detailed calculations.

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