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Letter to the Editor

A giant X-ray flare on the young star P1724

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Abstract. We present ROSAT X-ray observations as well as optical photometry and spectroscopy of the young stellar object P1724 in Orion. During a ROSAT observation in September 1992 P1724 showed a giant flare, where the X-ray count rate rose by more than a factor of 26 and then showed an exponential decay with a very long decay time of about 9 hours. P1724 is not a clear proper motion member to the Orion nebula association and, hence, its distance is not well established, but we present new spectroscopic and photometric evidence indicating that P1724 is a weak-line TTS associated with the Orion star forming region. For a distance of ≈ 500 pc, the total flare energy radiated in the ROSAT X-ray band (0.1 - 2.4 keV) is more than $\approx 5 \times 10^{37}$ erg. This is an order of magnitude above the highest energies of flares on young stars found so far, making this event the largest X-ray flare ever observed on a star.

Key words: Stars: flare – Stars: pre-main-sequence – Stars: coronae – X-rays: stars

1. Introduction

Since the observations of the EINSTEIN satellite young stars are known to show large X-ray flares with energetics vastly higher than for solar flares (e.g. Montmerle et al. 1983). In a systematic study of ROSAT observations of star forming regions and young clusters we found 36 large flares on young stars (Preibisch & Neuhäuser 1995) and that the largest flares are found in the youngest clusters. The most energetic X-ray flares on young stars observed so far seem to be the flare on the T Tauri star (TTS) LHα 92 in IC348 with a total flare energy of about 4×10^{36} erg (Preibisch et al. 1993) and the flare on ROX 20 in ρ Oph with $\approx 10^{36}$ erg (Montmerle et al. 1983). Only very long X-ray flares on RS CVn–type binaries show comparable energetics such as the HEAO-1 flare on DM UMa with (highly uncertain) $\approx 4 \times 10^{37}$ erg (Charles et al. 1979) and the ROSAT PSPC flare on CF Tuc (Kürster 1994) with 1.4×10^{37} erg (Kürster & Schmitt, in preparation).

P1724 (= HBC 452) is a relatively bright star ($V \simeq 11$ mag) located in Orion only 15′ north of the Trapezium. The spectrum is typical for a pre-main sequence star (Herbig & Bell 1988). Tagliaferri et al. (1994) (henceforth TCPRP) find very high lithium abundance, high rotational velocity ($v \sin i = 75$ km/s), no spectroscopic indications for binarity, and classify the star as a classical TTS associated with the Orion nebula. From an EXOSAT observation they derive an X-ray luminosity of $L_X \approx 4 \times 10^{31}$ erg/sec.

Our attention was drawn towards P1724 due to a giant X-ray flare during a ROSAT HRI observation in September 1992, originally detected and presented by Gagné et al. (1995). We used public ROSAT data of this star for a closer investigation of the flare and the X-ray spectrum. P1724 was investigated in several proper motion studies with quite different results (see Sec. 4), so that membership of P1724 to Orion and, hence, its distance remain unclear. We present new photometric and spectroscopic data, discuss its kinematics and conclude that P1724 is most likely a member of the Orion nebula association.

2. X-ray spectrum and luminosity

For this study we retrieved data from the ROSAT data archive and evaluated them with the EXSAS software package. The X-ray source position is in very good agreement with the optical position of P1724. In the finding chart of Jones & Walker (1988) another very faint star (JW 242) can be seen 4″ south of P1724. To exclude a possible misidentification we checked the validity of the X-ray source position in a deep HRI pointed observation from March 1991, where P1724 has an off-axis angle of only 6′. Comparing the positions of several X-ray sources with those of Guide Star Catalog stars (Lasker et al. 1990), we found very good agreement between the optical and X-ray positions. The nominal X-ray position is about 2″ north of P1724 and 7″ north of JW242. Since the distribution of

Send offprint requests to: Th. Preibisch photons in the X-ray image shows no deviation from that expected for a single point source, we conclude that the X-ray source indeed is P1724 and that JW242 does not contribute significantly to the X-ray emission. We performed the same check for the pointed observation in which the flare occurred and obtained a similar result. Beside JW242, no other star can be seen within 1′ around P1724 in the finding chart. So, we conclude that the identification of the X-ray source with P1724 is very reliable.

From a PSPC pointed observation in March 1991 where P1724 has a count rate of 0.16 counts/sec and shows no indication of variability we could extract an X-ray spectrum with more than 1200 source counts. After background subtraction and rebinning we fitted the spectrum with several models based on Raymond & Smith (1977) plasma spectra with interstellar extinction (Morrison & McCammon 1983). An isothermal plasma model clearly failed to reproduce the spectrum. A two temperature model gave an acceptable fit with $N_{\rm H} = 0.94^{+0.25}_{-0.14} \times 10^{21}\,{\rm cm}^{-2}$, $\log{(T_1/{\rm K})} = 6.9^{+0.1}_{-0.2}$, and $\log{(T_2/{\rm K})} = 7.5^{+0.2}_{-0.1}$. The emission meassure of the low temperature component was $4.4 \times 10^{53}\,{\rm cm}^{-3}$, that of the high temperature component $6.2 \times 10^{54}\,{\rm cm}^{-3}$, the reduced χ^2 of the fit was $\chi^2_{\rm red} = 1.35$. Assuming a distance of 500 pc, we obtained $L_{\rm X} = (8.4 \pm 0.8) \times 10^{31}$ erg/sec.

We also performed a fit with a continuous temperature distribution model, where the emission meassure EM is given by a power law $EM(T) = EM_0\,(T/T_{\rm max})^{\alpha}$ for T between 10^5 K and an assumed maximum temperature $T_{\rm max}$ (see Schmitt et al. 1990 for a discussion of this model). Our best fit (Fig. 1) gave $N_{\rm H} = 0.96^{+0.23}_{-0.20} \times 10^{21}\,{\rm cm}^{-2}$, $\log{(T_{\rm max}/{\rm K})} = 8.0^{+0.4}_{-0.2}$, $\alpha = 1.1^{+0.5}_{-0.3}$, $EM_0 = 7.1 \times 10^{54}\,{\rm cm}^{-3}$, and $\chi^2_{\rm red} = 1.33$. These parameters yield $L_{\rm X} = (8.5 \pm 0.8) \times 10^{31}$ erg/sec. This value places P1724 near the top of the X-ray luminosity function of the late type Orion stars with only few stars having comparable or higher X-ray luminosity (Gagné et al. 1995).

It should be noted that both models reproduce the extinction sensitive soft part of the spectrum very well (see Fig. 1) and give practically the same value for $N_{\rm H}$. This value is also roughly consistent with an extinction of $A_V \approx 1$ mag as derived from optical photometry. Hence, we think that fit results and X-ray luminosity are quite reliable. The X-ray luminosities in the other ROSAT observations were calculated by using the same ratio between count rate and X-ray luminosity as determined here and an PSPC to HRI count rate ratio of ≈ 2.4 appropriate for the spectral parameters found in the fits. As found in Sec. 4, P1724 has a K3 spectral type and a bolometric luminosity of $\approx 33 L_{\odot}$, so that we get $L_{\rm X}/L_{\rm bol} \approx 10^{-3}$, fully consistent with the values found both for the Orion nebula cluster members of that spectral type by Gagné et al. (1995) and for a large sample of ROSAT All-Sky Survey detected K-type TTS in Taurus–Auriga (Neuhäuser et al. 1995).

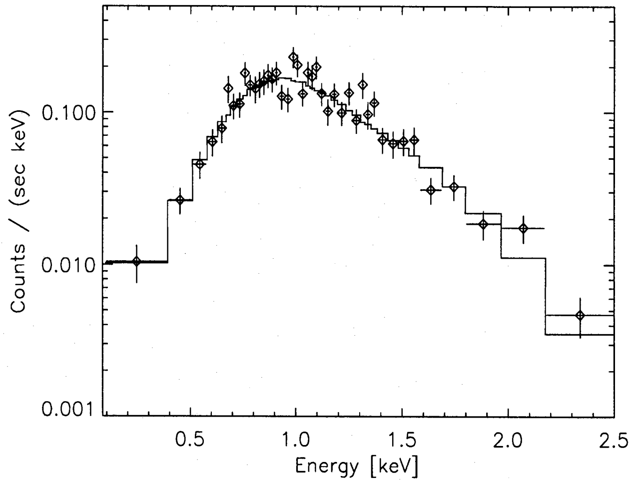

Fig. 1. X-ray spectrum of P1724. The diamonds with the error bars show the background subtracted spectrum, the solid line is the fitted model spectrum with the power law temperature distribution.

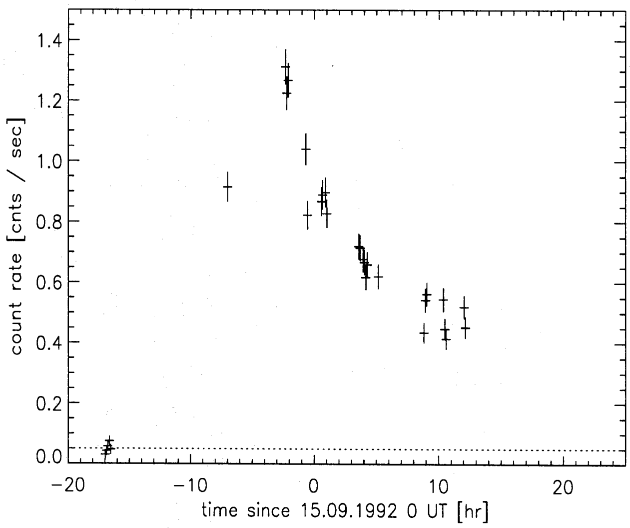

Fig. 2. Background subtracted lightcurve for P1724 from the HRI pointing in September 1992. The dotted line indicates the level of quiescent count rate as determined from additional observation intervals not shown here.

3. The flare

From all public ROSAT data of this star we extracted background subtracted X-ray lightcurves for P1724. We used 400 sec time bins as a compromise between the S/N of the lightcurves and the temporal resolution. In most lightcurves we could only find low level and irregular variability. This may be largely attributed to poisson counting noise since Kolmogorov-Smirnov tests gave probabilities of source variability below 0.9.

The large flare of September 1992 has originally been detected in the study of Gagné et al. (1995). The background subtracted X-ray lightcurve of this event is shown in Fig. 2. Due to large gaps in the lightcurve we can only give a rough estimate for the rise time of about 10 hours. Even a closer inspection of the data allows for the possibility that the peak of the flare occurred even before the observation interval with the maximum count rate. Hence, the values we derive for the peak luminosity and total flare energy may be only lower limits. Nevertheless, we do not expect this uncertainty to introduce significant errors in our results. During the flare the count rate rose by a factor of 26 compared to the pre-flare count rate of 0.055 ± 0.010 counts/sec. The decay phase of the flare can be fit rather well with an exponential decay curve and we derive a decay time of nine hours. The peak X-ray luminosity is 1.8×10^{33} erg/sec, the total flare energy radiated in X-rays is at least 5×10^{37} erg (neglecting the rise phase).

To infer some basic parameters about the flaring plasma in the corona of P1724 we modeled the lightcurve with a frequently applied flare model discussed in Pallavicini et al. (1990). In this model the plasma density n can be estimated from the decay time τ and the plasma temperature T by assuming only radiative cooling from the relation

$$\tau_{\rm rad} = \frac{3kT}{nP(T)}$$

As a typical plasma temperature we used $T \approx 3 \times 10^7$ K as determined by our spectral fits; this is also the typical temperature found during other stellar flares (see Preibisch & Neuhäuser 1995). With the radiative cooling function $P(T)$ given by van den Oord & Mewe (1989) we obtained a plasma density $n \approx 3 \times 10^{10}\,{\rm cm}^{-3}$, quite similar to the values found for large solar flares.

We calculated a characteristic volume V of the flaring plasma from EM and the density by assuming

$$EM \approx n^2\,V$$

and found $V \approx 2 \times 10^{35}\,{\rm cm}^3$. We are aware that these numbers may give only rough estimates, but they should have at least the correct order of magnitude.

To get an impression of the magnitude of this flare, we compare the parameters to that of solar flares. Even for the largest solar flares the total X-ray flare energy is $\lesssim 10^{32}$ erg, the volume of the flaring plasma $\lesssim 10^{30}\,{\rm cm}^3$. Thus, the quantities found for the flare on P1724 exceed solar values by more than 4 to 5 orders of magnitude. The volume of the flaring plasma is so large, that the active region in which the flare occurred must cover a considerable fraction of the stellar disk: Assuming a stellar radius of $\approx 9 R_\odot$ (see Sec. 4) and approximately half-spherical shape for the flare plasma, the region must extend over $\approx 50\%$ of the disk. Since even for the strongest solar flares the flare region covers only a few percent of the solar disk, this demonstrates the huge degree of coronal activity.

This flare seems to be the largest stellar X-ray flare observed so far. Even in the (as we think very improbable) case that P1724 is not associated with the Orion nebula and has a distance of only ≈ 140 pc (e.g. because it belongs to Taurus, see next section), these quantities reduce only about one order of magnitude and the flare still remains an outstanding event, representing one of the most energetic stellar flares.

4. Is P1724 a member of Orion?

We have obtained an optical spectrum of P1724 with the 1.8 m Perkins telescope of the Ohio-State-University in Flagstaff on December 23, 1990, displaying Hα in emission with equivalent width $W_\lambda({\rm H}\alpha) = 4$ Å and Lithium 6707.8 Å in absorption with W_λ(Li)= 0.47 Å(see Fig. 3); Ca H and K lines are also present (Tagliaferri, private communication). TCPRP report strong and variable Hα emission, typical for TTS. The Hα equivalent width found in several spectra varies between 1 and 2 Å (Tagliaferri, private communication) which is consistent with our observation. Hence, P1724 is a typical *weak-line* TTS. The fact that P1724 has not been detected by IRAS (Weaver & Jones 1992) confirms this classification. The strong Lithium line seen in our spectrum and reported by TCPRP and fast rotation indicate a very young age.

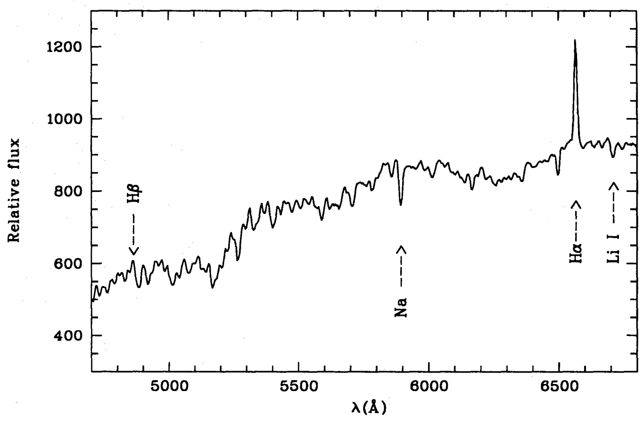

Fig. 3. Our spectrum of P1724 shows a K3-type star with Hα emission and Lithium absorption typical for weak-line TTS.

From our photometric data ($U = 13.11$, $B = 12.11$, $V = 10.72$, $R = 9.94$, $I = 9.24$ mag, and $A_V \approx 1$ mag) we determine a bolometric luminosity of 33 $L_\odot$ (at 500 pc). With $T_{\rm eff} = 4690$ K we can place P1724 into the HR diagram, and evolutionary tracks (Forestini 1994) yield an age of $\approx 2 \times 10^5$ yrs and a mass of $\approx 2.2\ M_\odot$. Both from the relation given by Barnes & Evans (1976) together with our photometric data and also from $L_{\rm bol} = 33\ L_\odot$ and $T_{\rm eff} = 4690$ K, we derive a stellar radius of $\approx 9\ R_\odot$. Comparing our photometric data and those in Herbig & Bell (1988) indicates variability. Also, the spectral type seems to vary as we have obtained K3 while TCPRP and Herbig & Bell (1988) report a G8 type. Spectroscopic and photometric variability is quite typical for a weak-line TTS and may be explained by dark spots on the surface caused by strong magnetic activity (e.g. Bouvier et al. 1993). The strong and variable X-ray emission also indicates that this object is a very young weak-line TTS. TCPRP have not found any indications for spectroscopic binarity. Also, the strong Lithium absorption line excludes the possibility that P1724 is a RS CVn-type contact binary.

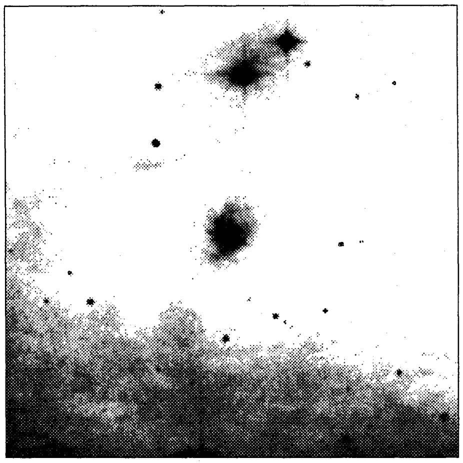

Fig. 4. Region around P1724 (the central object) reproduced from the SERC Southern Sky Survey; field of view $\approx 7' \times 7'$.

In optical images a small nebulosity can be found just around P1724 (see Fig. 4). It is *very* unlikely to see an active foreground star displaying several youth indicators *projected* onto a small nebula only a few arcminutes away from M42. Furthermore, from optical photometry and from the X-ray spectrum we consistently derive a rather high extinction of $A_V \approx 0.5 - 1$ mag. For a weak-line TTS one does not expect appreciable *circumstellar* extinction, so that P1724 is most likely located inside or behind the nebula. It is very unlikely that this nebula is not part of the Orion molecular cloud complex.

The membership of P1724 to Orion has been investigated in several proper motion studies, although with quite different results: McNamara & Huels (1983) give a membership probability P of 97%, Jones & Walker (1988) find $P = 42\%$, McNamara et al. (1989) and Van Altena et al. (1988) find $P = 0$. One possible conclusion from such vastly different results may be that either the epoch difference and/or the proper motion of P1724 are too small for a reliable evaluation, because the star is too far away. In any case, the most reliable proper motion to date is given by Van Altena et al. (1988) indicating that P1724 is not a proper motion member of Orion.

However, membership of a TTS to a star forming association cannot be assigned by proper motion alone. An object can be a member even with proper motion far off the mean velocity. The complex dynamical behaviour in dense stellar systems can produce single weak-line TTS with high velocities, called "run-away TTS" (Sterzik et al. 1995). For a few Trapezium cluster members Van Altena et al. (1988) have found proper motions that will place them several arcmin away from the Trapezium within less than 10^5 years. P1724's location just 15′ north of the Trapezium and its proper motion indicate that it may have been ejected from this cluster.

We conclude that P1724 is most likely a member of the Orion association. In any case, P1724 shows very interesting X-ray properties and additional optical and X-ray observations will be discussed in a future paper.

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