The discovery of the optical/IR counterpart of the 12 s transient X–ray pulsar GS 0834–43

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ABSTRACT
We report the discovery of the optical counterpart of the 12.3 s transient X–ray pulsar GS 0834–43. We re–analysed archival ROSAT PSPC observations of GS 0834–43 obtaining two new refined positions, ∼14′′ and ∼18′′ away from the previously published one, and a new spin period measurement. Based on these results we carried out optical and infra–red (IR) follow–up observations. Within the new error circles we found a relatively faint (V=20.1) early type reddened star (V–R=2.24). The optical spectrum shows a strong Hα emission line. The IR observations of the field confirm the presence of an IR excess for the Hα–emitting star (K′=11.4, J–K′=1.94) which is likely surrounded by a conspicuous circumstellar envelope. Spectroscopic and photometric data indicate a B0–2 V–IIIe spectral–type star located at a distance of 3–5 kpc and confirm the Be–star/X–ray binary nature of GS 0834–43.

Key words: binaries: general — stars: emission–line, Be — pulsar: individual (GS 0834–43) — Infrared: stars — X–ray: stars.

1 INTRODUCTION
Be/X–ray binary systems (BeXBs) represent the majority of the known High Mass X–ray Binaries (HMXBs) hosting an accreting rotating magnetic neutron star (White, Nagase & Parmar 1995). Phenomenologically, in the X–ray band, BeXBs can be divided into at least three subclasses: (i) bright transients which display giant X–ray outbursts up to $L_x=10^{38}$ erg s$^{-1}$ (Type II; Stella et al. 1986) unrelated with the orbital phase, with high spin–up rates, (ii) transients which display periodic outbursts of relatively high luminosity (L$_x \sim 10^{36}–10^{37}$ erg s$^{-1}$; Type I) generally occurring close to the periastron passage of the neutron star, and (iii) sources displaying no outbursts, but comparatively moderate variations (up to a factor of ∼10–100) and low–luminosity ($\leq 10^{36}$ erg s$^{-1}$) pulsed persistent emission (Negueruela 1998). 4U 0115+634 (P=3.6 s), V 0332+30 (P=4.4 s) and EXO 2030+375 (P=41.7 s) are all examples of the first two classes. Among the latter group, there are the well known X–ray pulsators X Per (P=835 s) and RX J0146.9+6121 (P=1455 s). Moreover, differences between the Galaxy and the Magellanic Cloud population of BeXBs have been studied and are probably due to the different star formation rate (see Stevens et al. 1999). B–emission (Be) spectral–type stars are characterized by high rotational velocities (up to 70% of their break–up velocity), and by episodes of equatorial mass ejection which might produce a rotating ring of gas around the star at irregular time intervals. At optical wavelengths, Be stars are difficult to classify due to the presence of the circumstellar envelope responsible for the emission–lines.

The hard X–ray transient GS 0834–43 ($l_{I I} \sim 262.0$, $b_{I I} \sim -1.51$) was discovered by the WATCH experiment onboard GRANAT in 1990 at a flux level of about 1 Crab in the 5–15 keV energy band (Sunyaev 1990). The source was later

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observed by GINGA (Makino 1990a, 1990b) and ROSAT as a part of the All Sky Survey (Hasinger et al. 1990) providing a much better positional accuracy (radius of 50′′). Moreover pulsations at a period of 12.3 s were observed during the GINGA, ROSAT and ART-P observations (Makino 1990c; Aoki et al. 1992; Hasinger et al. 1990; Grebenev & Sunyaev 1990). A target of opportunity ROSAT pointing performed in 1991 May allowed the source position to be determined with an uncertainty radius of 9′′ (Belloni et al. 1993). An optical follow-up observation of the stars within this error circle was performed at the ESO New Technology Telescope (NTT) in January 1991: no plausible optical counterpart was found down to a limiting magnitude of R∼23.5 (Belloni et al. 1993).

GS 0834–43 was also monitored by the Burst And Transient Source Experiment (BATSE) on the Compton Gamma Ray Observatory (CGRO) between April 1991 and July 1998. In particular seven outbursts were observed from April 1991 and June 1993 with a peak and intra–outburst flux of about 300 mCrab and <10 mCrab, respectively (Wilson et al. 1997). The recurrence time of 105–115 days was interpreted as the orbital period of the system. However, no further outbursts have been observed since July 1993 either with CGRO/BATSE and the All Sky Monitor (ASM) on board the Rossi X-ray Timing Explorer. All these findings suggested that GS 0834–43 is a new Be-star/X-ray binary system in an eccentric orbit (Wilson et al. 1997). However the lack of any plausible optical counterpart remained a key point against this interpretation.

In this paper we report the discovery of the optical counterpart of GS 0834–43 a V=20.4 Be spectral–type star. Starting from three public ROSAT PSPC observations of GS 0834–43 we obtained two new independent position measurements (uncertainty radius of 10′′). Within these new error circles we found a highly reddened star (V−R=2.24), the optical spectrum of which shows a strong Hα emission line. The optical counterpart was also observed in the IR showing that this star is by far the brightest object in the field (K′=11.4). Our findings together, obtained from observations in three different energy bands, support the Be–star/X-ray binary nature of GS 0834–43.

2 X–RAY OBSERVATIONS

The PSPC (0.1–2.4 keV) detector on board ROSAT observed the field including GS 0834–43 several times. In the ROSAT public archive there are 5 observations performed between April and December 1991. PSPC images were accumulated in the 0.5–2.0 keV range in order to reduce the strong and spatially inhomogeneous local background dominated by the soft X–ray emission from the Vela Supernova Remnant.

Both a sliding cell and a Wavelet transform–based detection algorithm were used in order to characterize the physical parameters (position, count rate, S/N ratio, etc.) of GS 0834–43 when detected, and to obtain a 3σ count rate upper limit in case of non-detection (Lazzati et al. 1999; Campana et al. 1999). Table 1 summarizes the results of this analysis.

GS 0834–43 was detected in May and December 1991 observations as a highly variable source: from 0.067 ct s−1 (May 5) up to 1.14 ct s−1 (December 21) corresponding to a variation of a factor of ∼20. We note that the flux we obtained for sequence 160062 is consistent with that inferred by Belloni et al. (1993). The source was also detected during sequence 160061 (see Table 1).

For each ROSAT observability window of GS 0834–43 we obtained an independent source position. These were determined to be R.A.=08h 35m 55.6, Dec.=−43°11′07″ (sequence 160061; May 91; equinox 2000), and R.A.=08h 35m 55.2, Dec. =−43°11′10″ (sequence 500127–8; Dec 17–21; equinox 2000). The statistical uncertainty corresponds to an error radius of only 0′.5 and 0′.2 for May 5 and December 17–21, respectively (90% confidence level). However due to the uncertainty in the boresight correction the error radius increases to 10″. We excluded from our position analysis sequence 160062 as the source was close to the circular support rib (radius of ∼20′) of the PSPC, resulting in a higher uncertainty (error radius of ∼20″). We note that the new refined positions of GS 0834–43 lie about ∼18″ (160061) and ∼15″ (500127–8) away from that obtained from sequence 160062 (Belloni et al. 1993; error radius 9″).

The ROSAT event list and spectra of GS 0834–43 were extracted from a circle around the best X–ray position (with an extraction radius corresponding to an encircled energy of 90% at the relevant off–axis angle). The photon arrival times were corrected to the barycentre of the solar system and a background corrected 1 s binned light curve accumulated for each observation. In order to maximize the period search sensitivity we analyzed only the observation with the highest statistics, namely sequence 500127–8 merged. A power spectrum was calculated over the entire observation duration following the method described by Israel & Stella (1996).

To increase the search sensitivity we searched for significant peaks in a narrow period interval centered around the period value detected by BATSE between 1991 December 28 and 1992 January 2 (Wilson et al. 1997; 12.307 s), thus only a few days after the ROSAT observation. We found a significant peak at a confidence level of 99.5% at a period of 12.307±0.003 s (90% uncertainties are used through out this paper). The pulsed fraction is 7%±2%, while the 0.1–2.4 keV pulse shape is well fitted by two sinusoidal waves (see Fig 1). A similar shape and pulsed fraction value were obtained at higher energies in 1991 December by BATSE (see Fig 5, 11 and 12 in Wilson et al. 1997).
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Table 1. ROSAT and ASCA observations of GS0834–43.

| Pointing Number | Instr. | Expos. (s) | Start Time | Stop Time | Count rate\(^{1}\) (ct s\(^{-1}\)) | Off-axis angle (\(^{\circ}\)) | Coordinates\(^{2}\) |
|-----------------|--------|------------|------------|-----------|-----------------------------|--------------------------|------------------|
| 500015          | PSPC   | 1854       | 1991 Apr 25 13:05 | 1991 Apr 25 13:30 | <0.20                       | 44                        | —                |
| 160062          | PSPC   | 2191       | 1991 May 05 16:41 | 1991 May 05 17:18 | 0.510±0.025                 | 22                        | see Belloni et al. 1993 |
| 160061          | PSPC   | 2005       | 1991 May 05 19:46 | 1991 May 05 20:21 | 0.067±0.018                 | 0                         | Dec.=–43\(^{\circ}\) 11\(^{\prime}\) 07\(^{\prime\prime}\)3 |
| 500015          | PSPC   | 8666       | 1991 May 06 06:40 | 1991 May 06 14:58 | <0.11                       | 44                        | —                |
| 500128          | PSPC   | 1316       | 1991 Dec 04 01:19 | 1991 Dec 04 01:41 | 0.237±0.023                 | 12                        | —                |
| 500127–8        | PSPC   | 18235      | 1991 Dec 17 11:31 | 1991 Dec 21 08:38 | 1.137±0.019                 | 12                        | R.A.=08\(^{h}\) 35\(^{m}\) 55\(^{s}\)2 |
|                 |        |            |             |           |                             |                          | Dec.=–43\(^{\circ}\) 11\(^{\prime}\) 07\(^{\prime\prime}\)3 |

42023000  GIS  35916  1994 Nov 28 07:45  1994 Nov 28 19:01  <0.01  10  —

\(^{1}\)  ROSAT PSPC and ASCA GIS locally background corrected count rates were obtained in the 0.5–2.0 keV and 0.5–10 keV energy bands, respectively. The ROSAT PSPC count rates are vignetting and PSF corrected. Errors are at 1\(\sigma\) level while upper limits at 3\(\sigma\).

\(^{2}\)  Equinox 2000. Error radius of 10\(\prime\) at 90\% confidence level.

Table 2. ROSAT PSPC spectral results for GS0834–43

| Parameter         | May 1991 | May 1991 | Dec 1991 |
|-------------------|----------|----------|----------|
|                   | (160062) | (160061) | (500127–8) |
|                   |          |          |          |
| Power-law model   |          |          |          |
| \(N_{H}\) (10\(^{22}\) cm\(^{-2}\)) | 2.3±0.3  | 1.1±0.8  | 2.3±0.3 |
| \(\Gamma\)       | 0.7 (fixed) | 0.7 (fixed) | 0.7±0.7 |
| \(F_{X}\) (10\(^{-11}\)) | 1.73     | 0.17     | 5.46     |
| \(L_{X}\) (\(N_{H}=0\); 10\(^{35}\)) | 2.58     | 0.13     | 8.05     |
| Blackbody model   |          |          |          |
| \(N_{H}\) (10\(^{22}\) cm\(^{-2}\)) | 2.0±0.3  | 0.8±0.8  | 2.0±0.3 |
| \(kT\) (keV)     | 1.0 (fixed) | 1.0 (fixed) | 1.0±0.3 |
| \(F_{X}\) (10\(^{-11}\)) | 1.71     | 0.16     | 5.44     |
| \(L_{X}\) (\(N_{H}=0\); 10\(^{35}\)) | 1.781    | 0.10     | 5.50     |
| Radius (km @ 5kpc) | 9.2     | 2.1      | 16.7     |

Note. — The X-ray fluxes (units are erg cm\(^{-2}\) s\(^{-1}\)) and the unabsorbed luminosities (units are erg s\(^{-1}\); a distance of 5kpc was assumed) refer to the 0.1–2.4 keV energy band.

The PSPC Pulse Height Analyser (PHA) rates were grouped so as to contain a minimum of 20 photons per energy bin. The spectra of sequences 160062, 160061 and 500127–8 (December 17–21) were fitted simultaneously. By using the brightest spectrum parameters as templates we fitted the three datasets keeping fixed the photon index and the temperature of the power-law and blackbody, respectively, for the two fainter spectra. A power-law (\(\Gamma=0.7\)) as well as a blackbody (\(kT=1.1\)keV) model gave good fits (\(\chi_{2}^{2}=1.09\) and \(\chi_{2}^{2}=1.11\), respectively).

The field of GS0834–43 was also observed on 1994 November 28 with the ASCA satellite. The source was not detected in the 0.5–10 keV band and a 3\(\sigma\) upper limit of 0.01 ct s\(^{-1}\) was inferred (corresponding to \(\sim 4\times 10^{-13}\) erg s\(^{-1}\) cm\(^{-2}\) assuming the best power-law model parameters of Table 2).

3 OPTICAL FOLLOW–UP

Based on the new X-ray positions, we carried out an optical follow–up from the ESO (La Silla, Chile) on 1999 January 18–20 with the 1.5 m Danish telescope and on March 13 with the New Technology Telescope (NTT).

Imaging and photometry in V, R and Gunn–i bands (200 s exposure time each) were performed on 1999 January 18–19 with the Danish Faint Object Spectrometer Camera (DFOSC), while spectroscopy of the brightest stars within the X-ray position uncertainty regions was obtained with the same instrument on 1999 January 19–20. The data were reduced using standard ESO-MIDAS procedures for bias subtraction, flat-field correction, aperture photometry and one dimensional stellar and sky spectra extraction. Profile fitting photometry was also carried out with DAOPHOT II (Stetson 1987). Cosmic rays were removed from each frame, and the spectrum corrected for the atmospheric extinction and flux calibrated. Figure 2 shows the field of GS0834–43 in the R filter (left panel) with the new X-ray uncertainty circles obtained from the 1991 May and December ROSAT observations superimposed. The earlier X-ray error circle (labelled as OLD) is also shown. Stars A and star C lie outside the new uncertainty regions (\(\sim 2\prime\) and \(\sim 6\prime\) away, respectively) while star D is the only object consistent with both circles and it is located at R.A. = 08\(^{h}\) 35\(^{m}\) 55\(^{s}\)4 and Dec. = –43\(^{\circ}\) 11\(^{\prime}\) 11\(^{\prime\prime}\)9 (equinox 2000; calibrated with DSS1 plates; uncertainty 1\(^{\prime\prime}\)). Photometry measurements for stars A, B, C and D are reported in Table 3.

Since the spectroscopic properties of star A were investigated by Belloni et al. 1993 (star A is a late spectral type star without any significant emission features), we focused our attention on star D. We obtained three low–resolution (11\(^{\prime}\)) spectra (30 min exposure time each; 1\(^{\prime}\)5 slit; 1\(^{\prime}\)2 seeing) of star D on 1999 January 20 with a grism covering the spectral range 5200–10000\(\AA\) (see upper line of Fig. 3). Note that the blue part of the spectrum, being relatively faint (\(V=20.4\)), was below the instrument sensitivity (telescope+CCD+grism). After reduction, the spectra were summed to increase the S/N ratio. Star D was also observed on 1999 March 13 with the ESO Multi–Mode Instrument (EMMI) mounted on the adaptor–rotator at the Nasmyth
Figure 2. R-band (left) and K′-band (right) images of the field of GS 0834–43 together with the new X-ray position uncertainty regions (10″ radius) obtained with the 1991 ROSAT PSPC observations. North is top, east is left. Stars D represents the proposed optical counterpart of GS 0834–43.

Table 3. Optical and IR results for star A, B, C and D

| Star | V   | R   | V−R | J   | H   | K′  | J−K′ |
|------|-----|-----|-----|-----|-----|-----|------|
| A    | 18.9| 17.8| 1.1 | 15.86| 15.96| 14.80| 1.06 |
| B    | 20.4| 19.0| 1.4 | 16.20| 15.24| 14.98| 1.22 |
| C    | 22.9| 20.8| 2.1 | 15.40| 13.81| 13.20| 2.11 |
| D    | 20.4| 18.2| 2.2 | 13.33| 12.26| 11.30| 1.94 |

Note — Optical magnitude absolute uncertainty is ∼0.2, IR is ∼0.02.

B focus of the NTT. A 30 min low-resolution (11 Å; 2″ slit; 2″ seeing) spectrum was obtained in the 4000–8500 Å range (see Fig. 3; lower line).

Due to its faintness, star D is difficult to study. The S/N ratio of the summed DFOSC spectrum is acceptable only above ∼6000 Å, while at >7500 Å the signal is dominated by interference fringes. The steep rise of the spectrum in the UV argues for a very hot and reddened object. The absence of strong forbidden lines rules out the possibility of a pre–main sequence object or a cataclysmic variable. Moreover the absence of strong absorption features points to an OB spectral–type star. The main features of the DFOSC spectrum are: (i) a strong Hα emission–line with equivalent width EW ∼ 30±2 Å, and (ii) pronounced interstellar absorption lines for Na II (5890 Å and 6270 Å). The Hα line shows an extended and asymmetric profile. At 11 Å spectral resolution, this might indicate a line splitting, possibly due to the presence of a disk. All this evidence clearly points to the association of this object with the X–ray source.

The EMMI spectrum has a slightly better S/N ratio and allows us to extend the spectral region into the 5500–8400 Å range. However, a precise spectral classification is not yet possible. A few SiII lines (e.g. the strong 5466.87 Å doublet) are recognizable, suggesting a B2 spectral type. However the uncertainty on the spectral classification is large, ranging from an O8e to a B3e star. Emission features corresponding to He I lines (e.g. 6678 and 7281 Å) are also evident, while the He I lines at 7065 and 7818 Å look filled in, as well as faint nebular [NII] lines on both sides of Hα, which most likely are due to the superposed emission from the Vela SNR (see Fig. 3). In the EMMI spectrum the Hα EW is ∼33±2 Å, while the FWZH is 41±3 Å, corresponding to a stellar wind terminal velocity Vwind ∼1800 km s⁻¹. Deep interstellar lines and bands are clearly visible in the star spectra, the Na D2 doublet having an EW of 4.1±0.8 Å.

Star B the position of which is still marginally consistent with the new X-ray error circle was observed on 1999 January 19. We obtained a low–resolution (11 Å) spectrum (1 h exposure time; 2″ slit; 1″7 seeing) with a grism covering the 3500–7000 Å spectral range. Star B is even more difficult to study being fainter than star D. Although the spectrum has a low S/N ratio, we detected large and deep absorption features typical of late type stars (probably an early M). Moreover no emission lines were visible in its spectrum.

4 IR OBSERVATIONS

Infrared observations were carried out on 1993 April 1 during service observing time using the Infrared Imager Spectrograph (IRIS) instrument (Allen 1993) mounted at the Cassegrain focus of the 3.9m Anglo–Australian Telescope (AAT), Siding Springs Observatory, New South Wales. Images were obtained in the J (60 s), H (20 s) and K′ (5 secs.) bands. The data were reduced using the Starlink Figaro software (Shortridge et al. 1998), and analysed using the PHOTOM package (Eaton & Draper 1998). The standard stars HD 84000 and HD 100231 were used for calibration purposes, giving absolute uncertainties of around 0.02 mag.
Taking the colours of a B2V star from Wegner (1994) as (V−K)=−0.67, (J−K)=−0.18 and (H−K)=−0.04, using the reddening relationships which gives E(J−K)/E(B−V)=+2.0 and thus E(B−V)=+4.0. Taking the parameter R_B=3.3 (R_B=E_V/ E(B−V)), we estimate an extinction of A_V=13.2 from the IR magnitudes.

5 DISCUSSION

The X-ray, optical and IR observations of the field of GS0834−43’s presented here, led to the identification of the optical counterpart of this 12s transient X-ray pulsar discovered in 1990. The measurement of the distance to GS0834−43 based on the optical data is hampered by the uncertainties in the spectral classification.

However some information can be inferred based on our optical and IR photometric measurements. The intrinsic V−R color for GS0834−43 is ∼−0.1 (assuming a main sequence star with spectral type in the O9−B3 range). Since the observed V−R is ∼2.25 the reddening should amount to E_V−R ∼ 2.35, and assuming a standard reddening law (Fitzpatrick 1999) this converts to A_R ∼ 7 (regardless of whether the reddening medium is uniformly distributed along the line of sight or is intrinsic to the source). Moreover from the X-ray spectral fits, we derive a N_H of 1−2 × 10^{22} which is in good agreement with the photometric reddening estimate (Bohlin et al. 1978). The observed magnitude of GS0834−43 is R ∼ 18.2 and the absolute R magnitude of a star with the assumed spectral type is within −2.5 < A_V < −5. Taking into account the effects of reddening, a distance modulus within 13.7 < m_−M < 16.2 can be derived. This translates to a distance of ∼5−17 kpc, well beyond the Vela SNR located at ∼500 pc. However the Galaxy edge in the direction of GS0834−43 is located at ∼6kpc, so we can put a limit on the spectral-type of star D assuming that it is placed at the Galactic border. For an O9, B0 or B2 dwarf star we obtain a reddened (A_R ∼ 7) R magnitude at 6 kpc (distance modulus of ∼ 14) of 16.5, 17 and 18.5, respectively. When compared with the observed R magnitude of 18.2 for star D, this suggests a B2Ve spectral-type star.

Also the derived E(B−V)=+4.0 from the IR data suggests a highly reddened object. Using the relationship for the contribution of the circumstellar (cs) environment derived by Fabregat and Reglero (1990), where E_{cs}=0.0049−0.00185 EW(Hα), and given the observed EW(Hα)∼30 Å, we estimate E_{cs} to be only 0.06 magnitudes. This suggests that the bulk of the extinction is interstellar rather than local to GS0834−43. This results confirm that the contribution of the disc (which is clearly present, given the large equivalent width inferred for Hα) to the observed IR colors is relatively small.

However the value of A_V∼13 derived from the IR observations differs significantly from that estimated from the optical data (where A_R∼7, and thus A_V∼9.4), suggesting that the object is either earlier in spectral class than B2, closer that 5−6 kpc, or possibly not a main sequence object. The observed magnitudes are similar to those of EXO 2030+375 (see e.g. Negueruela 1998), which is compatible with a B0V star at ∼3kpc or a B0III at ∼5kpc.

Based on both photometric and spectroscopic findings we conclude that star D is most likely a B0−2 V−IIIe star at a distance of 3−5 kpc. A more accurate distance and spectral classification will have to await detailed optical spectroscopic observations in the blue end of the spectrum.

For a distance of 5kpc and extrapolating the 0.1−2 keV ROSAT fluxes to the 1−10 keV band (we assume the spectral model fitted by Aoki et al. 1992 using Ginga data) we obtain an outburst peak luminosity L_X (1−10 keV) = 5−8 × 10^{36} erg s^{-1}. A somewhat higher luminosity (≈10^{37} erg s^{-1}) would be inferred by extrapolating the 20−100 keV BATSE peak flux reported by Wilson et al. (1997) to the 1−10 keV band. Such a peak luminosity is a typical value shown by X-ray pulsars which also display Type I out-
bursts (Stella et al. 1986; Negueruela 1998) occurring close
to the time of periastron passage and with a periodic recur-
rence given by the orbital period of the system.

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REFERENCES

Allen D., 1993, IRIS Users Manual, Anglo-Australian Observa-
tory manual 30a, version 2.5
Aoki T., Dotani T., Ebisawa K., et al., 1992, PASJ, 44, 641
Belloni T., Hasinger G., Pietsch W., et al., 1993, A&A, 271, 487
Bohlin R.C., Savage B.D., & Drake J.F., 1978, ApJ, 224, 132
Campana S., Lazzati D., Panzera R., et al., 1999, ApJ, 524, in
press
Eaton N. & Draper P.W., 1998, PHOTOM Users guide version
1.7, Starlink User Note 45-8
Fabregat J. & Reglero V., 1990, MNRAS, 247, 407
Fitzpatrick E.L., 1999, PASP, 111, 63
Grebenev S. & Sunyaev R., 1991, IAU Circ. 5294
Hasinger G., Pietsch W., & Belloni T., 1990, IAU Circ. 5142
Lazzati D., Campana S., Rosati P., et al., 1999, ApJ, 524, in press
Makino F., 1990a, IAU Circ. 5142
Makino F., 1990b, IAU Circ. 5139
Makino F., 1990c, IAU Circ. 5148
Negueruela, I., 1998, A&A, 338, 505
Shortridge K., Meyerdierks H., Currie M., et al., 1998, Figaro
Users guide version 5.4-0, Starlink User Note 86.16
Stella L., White N. E., & Rosner R., 1986, ApJ, 208, 669
Stetson P.B., 1987, PASP, 99, 191
Stevens J.B., Coe M.J., & Buckley D.A.H., 1999, MNRAS, in press

Sunyaev R., 1990, IAU Circ. 5122
Wegner W., 1994, MNRAS, 270, 229
White, N. E., Nagase, F., & Parmar, A. N., 1995 , in X-ray Bi-
naries, Eds. W.H.G. Lewin, J. van Paradijs & E.P.J. van den
Heuvel (Cambridge University Press), p.1 .
Wilson C.A., Finger M.H., Harmon B.A., et al., 1997, ApJ, 479, 388