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A possible detection of diffuse extended X-ray emission in the environment of the globular cluster NGC 6779

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ABSTRACT

We report the possible detection of diffuse X-ray emission in the environment of NGC 6779, and find the emission to be well aligned with the proper motion of the cluster. The position of the emission suggests we are observing heated ISM in the wake of the cluster that could be the result of an interaction between the intracluster medium and the halo gas surrounding it.

Key words: globular clusters: general – globular clusters: individual: NGC 6779 – X-rays: general – X-rays: ISM.

1 INTRODUCTION

When a globular cluster (GC) passes through the plane of the Galaxy any interstellar material it contains will be removed tidally and by ram pressure. Typically this will have occurred some 10^7–10^8 yr ago. Subsequently, the interstellar medium (ISM) of the GC will be replenished with material since a large fraction of the stars within the cluster will have progressed to a post-main-sequence evolutionary stage and therefore ejected matter into the intracluster medium. If each evolved star loses about $0.3\,M_\odot$ (Bergbusch & VandenBerg 1992; Richer et al. 1995) we would expect some 10^2–$10^3\,M_\odot$ of gas and some 0.1–1.0 $M_\odot$ of dust to be present in the cluster. Despite this, previous observations show that GCs are deficient in intracluster material (e.g. Penny, Evans & Odenkirchen 1997, and references therein; Hopwood et al. 1999). For example, the only secure detections of dust in GCs have been well below expected levels (Gillett et al. 1988, Origlia, Ferraro & Fusi Pecci 1996, Origlia et al. 1997, in 47 Tuc; Hopwood et al. 1998, in NGC 6356).

The current investigation was carried out to extend the work of Krockenberger & Grindlay (1995), searching for a bow shock in globular clusters resulting from an interaction between the cluster and the surrounding halo gas. Such an interaction has been proposed as the removal mechanism of any expected intracluster medium in GCs. Krockenberger & Grindlay (1995) found faint, soft, X-ray emission in 47 Tuc located along the direction of proper motion of the cluster and they suggested that this might be owing to a bow shock.

We report here the results of a search for the bow shock in NGC 6779 with the *ROSAT* High Resolution Imager (HRI).

2 NGC 6779

There are several criteria which make NGC 6779 a good candidate for these observations. These are as follows.

(i) The cluster lies at a Z-height of 1.4 kpc, somewhat lower in the halo than 47 Tuc (3.3 kpc). At such a position, the electron density is an order of magnitude higher ($4\times10^{-3}\,\mathrm{cm}^{-3}$ for NGC 6779, Nordgren, Cordes & Terzian 1992) than for 47 Tuc ($2\times10^{-4}\,\mathrm{cm}^{-3}$ and $1\times10^{-3}\,\mathrm{cm}^{-3}$ Nordgren et al. 1992 and Savage & de Boer 1981, respectively) and the interaction between cluster and halo gas must clearly be stronger as a result.

(ii) We have orbital data for NGC 6779 by Odenkirchen et al. (1997), determined from proper motions as measured with direct reference to the *Hipparcos* system. The observed proper motion is $+0.3\,\mathrm{mas\,yr^{-1}}$ in right ascension (RA) and $+1.4\,\mathrm{mas\,yr^{-1}}$ in declination (Dec.). If the interaction of the intracluster medium was with an external medium which itself moves like the material in the disc, then the tangential projection of the relative velocity between cluster and medium would be similar to the observed proper motion, since the peculiar velocity of the Sun is negligible. If however we assume that the interaction is with a medium that is at rest with respect to the Galaxy (perhaps more realistic), we have to add $+1.4\,\mathrm{mas\,yr^{-1}}$ in RA and $+1.6\,\mathrm{mas\,yr^{-1}}$ in Dec., to allow

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Table 1. Upper limits on the mass of gas and dust in the core of NGC 6779 (Hopwood et al., in preparation).

Equilibrium temperature (K)	Upper limits on the mass of gas in the core ($M_\odot$)	Upper limits on the mass of dust in the core ($10^{-3}\,M_\odot$)
40	2.0	6.8
70	3.0	3.5
100	4.0	2.4
150	5.6	1.5

Table 2. Positions (J2000) and count rates determined for the three point sources removed from the HRI image of NGC 6779.

Point source	RA	Dec.	count rate 10^{-3} count s^{-1}
1	19 16 14.5	30 19 01	2.79
2	19 15 54.8	30 11 01	1.16
3	19 15 50.2	30 00 56	1.97

for the motion of the observer with respect to the Galaxy. The proper motion is therefore $+1.7$ mas yr^{-1} in RA and $+3.0$ mas yr^{-1} in Dec. with respect to the Galactic rest frame. These data mean that we can be certain that the space velocity of the cluster (177 km s^{-1}) is of sufficient magnitude to induce a shock, using an adiabatic shock model (Spitzer 1978), and that the direction of the shock can be confidently matched with the proper motion of the cluster. Furthermore, the direction of the observed proper motion is not very sensitive to the assumed motion of the external medium.

(iii) The size of the cluster (tidal radius, $r_t = 12'.0$, Webbink 1985) is sufficiently small to fit well inside the HRI field of view. At the cluster distance of 9.8 kpc (Pryor & Meylan 1993), the tidal radius is 1.1×10^{20} cm.

(iv) Our sub-millimetre observations of NGC 6779 taken with SEST and SCUBA, have confirmed that this cluster is deficient in intracluster material (Hopwood et al., in preparation). Table 1 gives upper limits on both the gas and dust content in the core of this cluster, if the equilibrium temperature of the material is at 40, 70, 100 and 150 K (Angeletti et al. 1982). The upper limits on the mass of gas were determined from CO observations, and converted using the CO-to-H_2 relationship given by Bujarrabal, Fuente & Omont (1994).

3 OBSERVATIONS AND REDUCTIONS

NGC 6779 was observed by the *ROSAT* HRI between 1998 March 23 and 1998 April 22, for a total integration time of 21 169 s and a dead time corrected exposure of 20 972.48 s. The HRI is a two-dimensional position-sensitive detector based on microchannel plates, that detects single X-ray photons in the range 0.1–2.4 keV, and determines their positions and times of arrival. The instrument has a field of view of 38 arcmin (square) and a spatial resolution of 5 arcsec (full width at half-maximum, hereafter FWHM).

The data were reduced using the EXTENDED SOURCE ANALYSIS SOFTWARE (ESAS) originally developed by Snowden et al. (1994), and recently extended by Snowden & Kuntz (private communication) to include a model for the HRI particle background. For objects greater than a few arcmin in extent, these routines allow a more realistic and useful reduction of *ROSAT* Position Sensitive Proportional Counter and HRI data than the standard ASTERIX or IRAF/PROS reduction packages (NGC 6779 covers a significant fraction of the HRI field of view). ESAS provides the best available modelling and subtraction of various non-cosmic X-ray background emission components, and corrections for exposure, vignetting and variations in detector efficiency.

To reduce the data, we cast the observed events into event images, selecting a radius restriction of 17.5 arcmin and producing an observation light curve. We then created exposure and background images in sky co-ordinates, using a model to account for the HRI particle background (Snowden 1998), the former image corrected for vignetting and variations in the quantum efficiency of the detector at this stage. The software created a model particle background light curve, fitted this model to the observed light curve and from this, cast the model particle background counts into images. The fit to the light curve gave a reduced χ^2 value of 1.34, indicating a relatively good fit to the data.

We then used the event and exposure maps to search for point sources in the field. The software carries out this procedure using a sliding box algorithm, although the box is actually a circle, with the radius being a function of off-axis angle [since the point spread function (PSF) varies with off-axis angle]. We set the statistical significance to be 4σ when searching for such features, and three point sources were detected in the field. Details of these are given in Table 2. Finally, the event, model particle background count and exposure images were combined to create an intensity image. This was carried out by subtracting the background map from the event map pixel-by-pixel, and dividing through by the exposure map. The point sources were then removed.

Fig. 1 is a 30 arcmin^2 field centred on NGC 6779 from the DSS archive at the European Southern Observatory. The optical DSS2 data have been overlaid with the X-ray contours from the intensity image, which has been blurred using a Gaussian mask with a FWHM of 2 arcmin. The point sources identified in Table 2 are marked on Fig. 1.

4 DATA ANALYSIS AND RESULTS

The presence of diffuse extended X-ray emission is apparent from the *ROSAT* image given in Fig. 1, in the direction of decreasing RA and decreasing Dec. The emission is well aligned with the proper motion of the cluster. The emission region is ~15 arcmin in length (in the direction of the proper motion vector) and ~9 arcmin in width (in the direction orthogonal to the proper motion vector). There is also diffuse extended X-ray emission to the left of the image which can be attributed predominantly to the western edge of the superbubble in Cygnus (see fig. 2 in Cash et al. 1980), although detector edge effects may be also significant.

To find the count rate over the emitting region, we placed several square boxes of size 11.1 arcmin^2 over the area of interest on the unsmoothed image, i.e. the $15' \times 9'$ region mentioned above, and summed over this area. A 11.1 arcmin^2 box was chosen as a compromise since it is ample enough in size to give good statistics, and fits well into the dimensions of the emitting region ($15' \times 9'$). We found a count rate of 0.127 ± 0.004 count s^{-1}. We then placed identical boxes over several random areas of background (around the periphery of the image given in Fig. 1) and found this to give a mean count rate of 0.090 ± 0.004 count s^{-1}. Combining the two results we found that the region of diffuse X-ray emission corresponded to a total count rate of 0.038 ± 0.006 count s^{-1}. If we take the column density to this

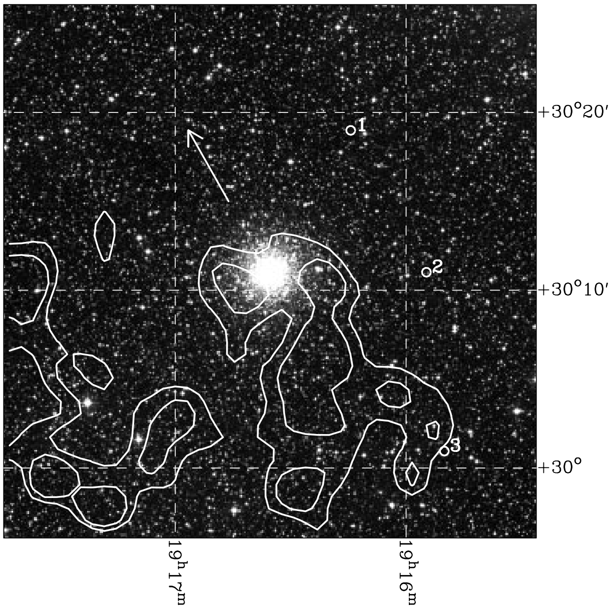

Figure 1. The resulting smoothed image of NGC 6779 as observed with the *ROSAT* HRI camera. The outer and inner contours correspond to count rates of 1.19×10^{-3} and 1.30×10^{-3} count s^{-1} arcmin^{-2}, which are at significance levels of 4.5 and 6 σ respectively, above the mean background. The tangential motion of the cluster with respect to the Galactic rest frame is marked with an arrow. The point sources identified in Table 2 are marked on the figure.

cluster to be 1.5×10^{21} cm^{-2} (Zombeck 1990), and assume a Raymond–Smith plasma model (Raymond, Cox & Smith 1976) with a temperature of 0.08 keV (Spitzer 1978) corresponding to the space velocity of the cluster (177 km s^{-1}), the count rate converts to a total flux of 2.4×10^{-12} erg cm^{-2} s^{-1} in the HRI passband, over the emitting region.

We rule out the possibility that the emission we observe is owing to random fluctuations in the soft X-ray background for two reasons. First, Warwick et al. (1998) observed the Galactic halo with the *ROSAT* PSPC and found typical fluctuations in amplitude of $\sim 5 \times 10^{-5}$ count s^{-1} arcmin^{-2} over a scale of 15–20 arcmin, much smaller than the variations in flux seen in Fig. 1 (although we should note that the amplitude of the flux variations in the PSPC will not map directly on to the corresponding fluctuations in the HRI). Secondly, the detection and the coincidence of the location of the emission with respect to the proper motion vector, lead us to conclude that an interaction between cluster and halo is the most likely cause of the emission.

5 DISCUSSION

The position of the diffuse X-ray emission suggests that we are not observing a bow shock since this would be apparent ahead of the cluster, but the ISM of the halo in the wake of the cluster which has been heated, possibly as a result of the interaction between the cluster and the halo medium. We comment here on the significance of the detection of diffuse X-ray emission in the environment of NGC 6779 and discuss two possible explanations.

(i) If we assume that the halo gas is adiabatically shocked by the interaction with the intracluster medium, then we would expect the post-shock temperature of the gas to be 9.4×10^5 K (Spitzer 1978) corresponding to the space velocity of the cluster (177 km s^{-1}), and the post-shock electron density of such material to be 0.016 cm^{-3} (corresponding to the intial electron density of 0.004 cm^{-3}, Nordgren et al. 1992). We use a Raymond–Smith plasma model to find the flux we would expect to observe over a volume of gas approximately 10^{60} cm^3 (see Section 2) in size. We use the post-shock temperature and electron density, distance to the cluster and halo abundances for 18 elements given by S. Ryan (private communication) in this calculation. We find the flux in such a model to be 7.0×10^{-13} erg cm^{-2} s^{-1}, slightly smaller than that observed by the HRI. In order to match the model to our observation, we would require an ambient (pre-shock) electron density of 7.7×10^{-3} cm^{-3}, a factor of two higher than that assumed.

The electron densities given by Nordgren et al. (1992) are derived from 61 pulsar measurements in and around the disc of the Galaxy with the addition of 29 pulsars in globular clusters at high Galactic latitudes. The deviation in the dispersion measures used by Nordgren et al. to derive the mean dependence of electron density on *Z*-height is sufficiently large that deviations of a factor $\sim$2–3 around the mean are not unreasonable so that a higher pre-shock electron density for the halo gas than this relationship predicts is possible.

(ii) Secondly, we assume that the cluster contains gas only out to some radius, much smaller than the tidal radius of the cluster, that is able to interact with the halo medium, and therefore treat the emission region given in Fig. 1 essentially as a series of shocked volumes of gas following the motion of the cluster along its orbit. This is perhaps more realistic since we would expect the gas to be distributed throughout the cluster in the same way as the stars. We assume the emitting area is the result of roughly two consecutive passages of a volume of gas 4.6 arcmin in radius since this is half the width of the shocked region (see Section 4) we observe in Fig. 1. Re-analysing the data accordingly, we find the flux emitted over a volume of shocked gas of this size to be 1.2×10^{-12} erg cm^{-2} s^{-1} in the HRI passband. As above, we use a Raymond–Smith plasma model to find the flux we would expect to observe if the halo medium has been adiabatically shocked by such a volume of gas. We find the flux in such a model to be 1.7×10^{-13} erg cm^{-2} s^{-1}, again requiring the ambient electron density to be higher (1.0×10^{-2} cm^{-3}). Once again, although this is a factor of 2.5 greater than the estimated pre-shock electron density, it lies within the deviation of $\sim$2–3 around the mean from pulsar dispersion measurements made by Nordgren et al. (1992).

In this case, the cluster has passed through two paths 4.6 arcmin in length and the gas has remained shocked. We therefore calculate the cooling time-scale for the post-shock gas to deduce whether it is possible for the gas to remain shocked for a longer period of time than it takes for the cluster to move 4.6 arcmin along its orbit. We find the cooling time-scale to be approximately 2×10^6 yr, $\sim$21 times longer than the time it takes the cluster to move this distance. In this calculation, we take the temperature of the gas to be 9.4×10^5 K corresponding to the space velocity of the cluster, and use an electron density of 4.0×10^{-2} cm^{-3}, since this is the value required to fit a Raymond–Smith plasma model to our observations. If we decrease the electron density as originally anticipated, the cooling time-scale gets longer, and we still have consistency.

6 CONCLUSIONS

We have reported the possible detection of diffuse X-ray emission in the environment of the globular cluster NGC 6779. We found the emission to be well aligned with the proper motion vector of the cluster. The observed count rate from the emitting region corresponds to a total flux of $2.4 \times 10^{-12}\,\mathrm{erg\,cm^{-2}\,s^{-1}}$ in the HRI passband, if a Raymond–Smith plasma model is assumed. The position of the emission suggests we have observed heated ISM in the wake of the cluster, possibly a result of the interaction between the cluster and the halo medium.

If the diffuse X-ray emission is the result of an adiabatic shock between the intracluster medium and the halo medium, then we require the electron density of the halo to be higher than that derived from pulsar measurements by Nordgren et al. (1992).

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REFERENCES

Angeletti L., Capuzzo-Dolcetta R., Giannone P., Blanco A., Bussoletti E., 1982, MNRAS, 199, 441
Bergbusch P. A., VandenBerg D. A., 1992, ApJS, 81, 163
Bujarrabal V., Fuente A., Omont A., 1994, A&A, 285, 247
Cash W., Charles P., Bowyer S., Walter F., Garmire G., Riegler G., 1980, 238, L71
Gillett F. C., de Jong T., Neugebauer G., Rice W. L., Emerson J. P., 1988, AJ, 96, 116
Hopwood M. E. L., Evans A., Penny A., Eyres S. P. S., 1998, MNRAS, 301, L30
Hopwood M. E. L., Eyres S. P. S., Evans A., Penny A., Odenkirchen M., 1999, A&A, 350, 49
Krockenberger M., Grindlay J. E., 1995, ApJ, 451, 200
Nordgren T. E., Cordes J. M., Terzian Y., 1992, AJ, 104, 1465
Odenkirchen M., Brosche P., Geffert M., Tucholke H. J., 1997, New Astron., 2, 477
Origlia L., Ferraro F. R., Fusi Pecci F., 1996, MNRAS, 280, 572
Origlia L., Scaltriti F., Anderlucci E., Ferraro F. R., Fusi Pecci F., 1997, MNRAS, 292, 753
Penny A. J., Evans A., Odenkirchen M., 1997, A&A, 317, 694
Pryor C., Meylan G., 1993, in Djorgovski S. G., Meylan G., eds, Structure and Dynamics of Globular Clusters, ASP Conf. Ser. Vol. 50. Astron. Soc. Pac., San Francisco, p. 357
Raymond J. C., Cox D. P., Smith B. W., 1976, ApJ, 204, 290
Richer H. B. et al., 1995, ApJ, 451, L17
Savage B. D., de Boer K. S., 1981, ApJ, 243, 460
Snowden S. L., McCammon D., Burrows D. N., Mendenhall J. A., 1994, ApJ, 424, 714
Snowden S. L., 1998, ApJS, 117, 233
Spitzer L., 1978, Physical processes in the interstellar medium. Wiley-Interscience, Chichester NY
Warwick R., Hutchinson I., Willingale R., Kuntz K., Snowden S., 1998, Lecture Notes in Physics, 506, 321
Webbink R. F., 1985, in Goodman J., ed., Proc IAU Symp. 113, Dynamics of Star Clusters. Reidel, Dordrecht, p. 541
Zombeck M. V., 1990, Handbook of space astronomy and astrophysics, 2nd edn. Cambridge Univ. Press, Cambridge

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