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DETECTION OF AN ULTRAVIOLET AND VISIBLE COUNTERPART OF THE NGC 6624 X-RAY BURSTER[1]

I. R. KING,[2] S. A. STANFORD,[2] R. ALBRECHT,[3,4,5] C. BARBIERI,[6] J. C. BLADES,[7] A. BOKSENBERG,[8] P. CRANE,[4]
M. J. DISNEY,[9] J. M. DEHARVENG,[10] P. JAKOBSEN,[11] T. M. KAMPERMAN,[12] F. MACCHETTO,[5,7]
C. D. MACKAY,[13] F. PARESCE,[5,7,14] G. WEIGELT,[15] D. BAXTER,[7] P. GREENFIELD,[7]
R. JEDRZEJEWSKI,[7] A. NOTA,[7] W. B. SPARKS, AND C. SOSIN[2]

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ABSTRACT

We have detected, in images taken with the *HST* FOC, the UV and optical counterpart of the X-ray source 4U 1820−30 in the globular cluster NGC 6624. Astrometric measurements place this object 2 σ from the X-ray position of 4U 1820−30. The source dominates a far-UV FOC image and has the same flux at 1400 Å as was seen through the large *IUE* aperture by Rich et al. (1993). It has a B magnitude of 18.7 but is not detected in V. It is 0".66 from the center of NGC 6624, a fact that may change the interpretation of the $\dot{P}$ of the 11 minute binary orbit. The flux drops between 1400 and 4300 Å at a rate that is nearly as steep as that of a Rayleigh-Jeans curve. The flux is far too large to come from the neutron star directly but could accord with radiation from a heated accretion disk and/or the heated side of the companion star.

Subject headings: globular clusters: individual: NGC 6624 — stars: neutron — ultraviolet: stars — X-rays: bursts — X-rays: stars

1. INTRODUCTION

The X-ray source 4U 1820−30, near the center of the globular cluster NGC 6624, is one of the most interesting of low-mass X-ray binaries. It is a "burster" (Grindlay et al. 1976), it has a binary period of 11 minutes (Stella, Priedhorsky, & White 1987a), it shows quasi-periodic rapid oscillations (Stella, White, & Priedhorsky 1987b), and its binary period has an enigmatically negative time derivative (van der Klis et al. 1993).

The X-ray source has not previously been identified with any optical counterpart. Part of the difficulty is that whereas the X-ray position is known within better than a second of arc (Hertz & Grindlay 1983), the position of the cluster center is uncertain. Two determinations (Shawl & White 1986 and Hertz & Grindlay 1985) differ by nearly 5".

[1] Based on observations with the NASA/ESA Hubble Space Telescope, obtained at the Space Telescope Science Institute, which is operated by AURA, Inc., under NASA contract NAS 5-26555.

[2] Astronomy Department, University of California, Berkeley, CA 94720.
[3] Space Telescope European Coordinating Facility.
[4] European Southern Observatory, Karl-Schwarzschild Strasse 2, D-8046 Garching, Germany.
[5] Affiliated to the Astrophysics Division, Space Science Department of ESA.
[6] Osservatorio Astronomico di Padova, Vicolo Osservatorio 5, I-35122 Padova, Italy.
[7] Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218.
[8] Royal Greenwich Observatory, Madingley Road, Cambridge CB3 0EZ, United Kingdom.
[9] Department of Physics, University College of Cardiff, PO Box 713, Cardiff CF1 3TH, Wales, United Kingdom.
[10] Laboratoire d'Astronomie Spatiale du CNRS, Traverse du Siphon, Les Trois Lucs, F-13012, Marseille, France.
[11] Astrophysics Division, Space Science Department of ESA, ESTEC, NL-2210 AG, The Netherlands.
[12] SRON-Space Research Utrecht, Sorbonnelaan 2, 3584 CA Utrecht, The Netherlands.
[13] Institute of Astronomy, Cambridge, Madingley Road, CB3 0HA, United Kingdom.
[14] Osservatorio Astronomico di Torino.
[15] Max-Planck Institut für Radioastronomie, Auf dem Hügel 69, D-5300 Bonn 1, Germany.

As part of a program with the *Hubble Space Telescope's* Faint Object Camera (FOC) to study the color-magnitude array and stellar distributions in the cluster, a far-UV exposure of the cluster center was also included. This *Letter* reports the discovery of the UV and optical counterpart of the X-ray source and presents data on its properties.

2. OBSERVATIONS

NGC 6624 was observed on 1992 August 13. The FUV exposure was made with the f/96 camera of the FOC, through filter F140W. (For details of the camera and its filters, see Paresce 1992; for its performance in orbit see Greenfield et al. 1991). Exposures in fine lock were made in two successive *HST* orbits, with a total exposure time of 3594 s. The format was 512 × 1024 pixels, each of them zoomed to 50 × 25 μm, giving a total field of 22" × 22". This format has a counting capacity of 255 in each pixel; 3 pixels in a bright object near the center were found to have "rolled over" and were corrected by hand to their true values. The brightness distribution, which had had a hole in it, then recovered its smooth peak. Each pixel was first divided into two equal ones, so as to change the image to a properly shaped 1024 × 1024, and the images were geometrically corrected and flatfielded by the Routine Science Data Processing "pipeline."

As part of the same program, images were also taken through the F430W ("B") and F480LP ("V") filters, in both cases with 3 mag of neutral-density filter, to avoid saturation. Also, to avoid what would have been a hopeless rollover problem, these images were taken in the conventional 512 × 512 f/96 format, so that they cover only the central quarter of the F140W image.

3. THE UV SOURCE AND ITS LOCATION

The FUV image (Fig. 1) is dominated by a single bright object close to the center. The object is as narrow as a point-spread function (PSF) and is evidently a star.

Our first task was to see if this coincided with any star in the visible images. The images were easy to align, because many of

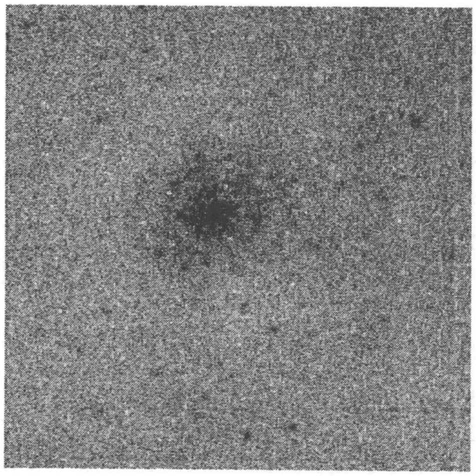

FIG. 1

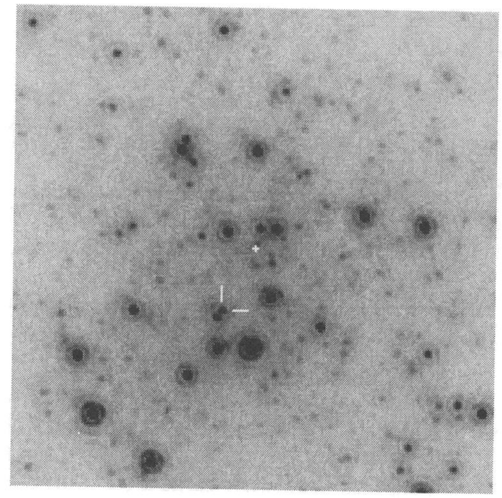

FIG. 2

FIG. 1.—The central quarter of the 22″ × 22″ image of the center of NGC 6624 taken with the FOC f/96 and F140W. Nearly all the faint images are red giants seen through the redleak. In this and in Fig. 2, the vertical direction is in position angle 221°.

FIG. 2.—A 4″.5 × 4″.5 central region of the F430W image. Our adopted cluster center is marked by a white cross at the center of the figure. The X-ray source is also marked. The sharpness of the core of the PSF is evidenced by the Airy rings that can be seen around the images of the brighter stars.

the red giants of the cluster showed clearly in the F140W image because of the redleak of the filter. When the lineup was performed, the FUV star fell, within about a tenth of a pixel, or 2 mas, on a well-exposed star in the F430W image that was too faint to be found at all in the F480LP image. The search for the blue star in the F480LP image is made quite difficult by the presence of a red giant only 0″.08 away. We fitted a PSF to the red star and subtracted the star out but were still unable to detect any sign of the blue star in the *V* image. Above the expected white dwarf level, blue stars are not known to exist otherwise in NGC 6624, which has only a red stub of a horizontal branch; there seems little doubt that our blue star is the FUV source.

The central region of the cluster in F430W is shown in Figure 2 where the blue star and the center (see below) are marked. The blue star is 0″.66 from our chosen cluster center, in position angle 13°.

4. THE POSITION OF THE CLUSTER CENTER

It is important to know whether the FUV source coincides with the X-ray source. As previously noted, this question can be answered only by redetermining the position of the cluster center with greater accuracy. This determination consists of two steps: first, finding the position of the center within the cluster, and second, referring this point to a standard astrometric system.

It is clear from Figure 2 that the exact position of the cluster center is far from obvious. With ground-based resolving power it has been customary to find photometric centroids of globular clusters, but Calzetti et al. (1993) have recently shown that a better approach is to weight all stars equally—a procedure that the greater resolution of *HST* allows. To find a cluster center, they used a form of mirrored autocorrelation, using coordinates of individual stars rather than the amount of light in the original image; the autocorrelation at a given point was determined by the number of stars falling within a certain limiting radius of the mirror position of each target star. The resulting center thus escapes being biased by the more luminous stars. As an independent way of determining the cluster center, they also verified that the star counts around their center were azimuthally smooth.

We calculated a mirrored autocorrelation by a somewhat different procedure from that used by Calzetti et al. First, we took a magnitude list that had been produced from the F430W image in a related study, and chose a faint cutoff conservatively, so as to get a spatially unbiased sample. We then created a new image in which each star is a Gaussian with a FWHM of 50 pixels, and all stars are equally bright. We did a mirrored autocorrelation (with a data window of 150 pixels) on this Gaussian image at each of the points of a grid, fitted a least-squares paraboloid to the values, and took as our center the vertex of the paraboloid, which was determined with a formal error of less than a pixel. We feel that our procedure is preferable to theirs, because it gives much better emphasis to the central peak of number density, which best determines the cluster center.

Independently, we also used a form of the azimuthal-smoothness method to determine the center. At each point of a grid we tabulated, in eight angular bins around the grid point, the number of stars within 120 pixels. We then calculated a χ^2 figure of merit that indicated how well this azimuthal distribution was fit by a constant. We fitted the resulting grid of values with a paraboloid and determined the vertex in much the same way as in the previous method. The two methods gave results that agreed within 1.5 pixels. In each case we experimented with different reasonable values of the window size (and the Gaussian width); changes were of the order of a pixel. We chose a rounded-off compromise value as the center and believe that it is reliable to a pixel or two (1 pixel = 22 mas).

Our next step was to use a ground-based CCD image of NGC 6624 to tie to a larger photographic image that contained astrometric standards. First we had to locate the cluster center on the CCD image, which was taken in 2″ seeing. To do so, we degraded the *HST* image in resolution by a factor of 25, still leaving it a little less blurred than the ground-based image.[16] We then resampled so that the two images had the

[16] Detractors of the performance of *HST* should take note of this number.

same pixel size, rotated the CCD image into the same orientation as the *HST* image and found the offset of the two images by cross-correlation. It was then possible to mark the cluster center on the CCD image.

For astrometric tie-in we used a 2048 × 2048 GASP image supplied by the Space Telescope Science Insitute. (GASP is their name for images extracted from the archive of digital tracings of the plates of their *HST* guide-star survey.) Arnold Klemola was kind enough to provide us with a listing of stars in that region from the magnetic-tape catalog of the Astrometric Catalog Reference Stars; 16 of these stars fell within our field. It was possible to measure 12 stars on both the CCD image and the guide star–tracing image. These were used to calculate a linear transformation between the coordinate systems of the two images, and finally to calculate the right ascension and declination of the cluster center from the known positions of the reference stars, using astrometric programs written by S. Djorgovski. Our transformation from the CCD to the astrometric image had residuals of about 0.″2 for each star, so that a transformation based on 12 stars should have an error of less than 0.″1. We feel that the uncertainties in our various steps leave the final position with an uncertainty of one or two tenths of an arcsecond, arising largely from the relating of the *HST* image to the CCD image.

5. IDENTIFICATION

The various positions are listed in Table 1. The position of our optical/UV source differs from the X-ray position by only 2 σ of the latter. This closeness, along with the steep spectral slope derived below, leaves little doubt that our star is the optical counterpart of the X-ray binary.

Until recently it might have been thought that the best position of 4U 1820−30 is the VLA position measured by Johnston & Kulkarni (1992). It now appears, however, that this radio source has such a steep spectrum that it is actually one of the pulsars reported by Biggs et al. (1990) (private communications from A. Fruchter, S. Kulkarni, and A. Lyne). Moreover, A. Lyne now finds (private communication) that one of the pulsars has a position that is quite close to that of Johnston & Kulkarni, which is 2″ away from our position of the LMXB counterpart.

6. FLUX VALUES

To calibrate our UV observations we assumed that our extremely blue source has a nearly Rayleigh-Jeans spectrum (as verified below; note that we tried spectra with both λ^{-4} and λ^{-3}, and found that the difference between the two results was trivial), and integrated the product of this spectrum with the nominal sensitivities of the telescope and f/96 camera, and the transmission of the filter. This calculation showed that a source with this spectrum would give, overall, 1 count per second through F140W if it had $F_\lambda = 1.90 \times 10^{-16}$ ergs cm^{-2} s^{-1} Å^{-1} at 1400 Å. On-orbit calibrations have shown (Sparks 1991) that this setup has only 0.75 of nominal sensitivity, but it has recently been found that the full-field format that we used is 10% more sensitive than the more usual 512 × 512 format with which the calibrations were carried out (P. Greenfield, personal communication). We take a combined factor of 0.825 and revised our unit count rate F_λ to 2.30 × 10^{-16} ergs cm^{-2} s^{-1} Å^{-1}.

The total F140W counts in the X-ray source cannot be derived by simply adding up the counts over an area large enough to encompass the entire PSF, because too many redleak images of red giants are included in this area, and the result would also be too sensitive to the sky correction that was made. Instead, aperture photometry was performed on a relatively small central region and normalized to the total light. For this a growth curve is needed, and this posed a problem. An older growth curve clearly did not fit this image, presumably because of a difference in the telescope (OTA) focus. Since the only PSF available for the period of observation was saturated in its center, we synthesized a PSF using the Tiny Tim software of Krist (1993). Because the resulting PSF was not a perfect match to the profile of the bright UV object, normalization of different apertures gave different totals. In the range of radii from 3 to 15 pixels, which we believe to be reasonable aperture sizes to work with, estimates of the total ranged from 35,000 to 46,000 counts. We have adopted a compromise value of 40,000, and believe it to be within 10% of the correct value. The total count rate is thus 11.1 counts s^{-1}, giving an F_λ of 2.6 × 10^{-15} ergs cm^{-2} s^{-1} Å^{-1}.

Our determination of the blue F_λ was quite different. Here we had two opportunities, one by use of the method just described and another by scaling to ground-based data for the same cluster.

For the nominal-sensitivity calculation we again assumed a nearly Rayleigh-Jeans spectrum and found that through the filters F430W + 1ND + 2ND such a source would give 1 count s^{-1} if it had a flux of 3.23 × 10^{-17} ergs cm^{-2} s^{-1} Å^{-1}. For the source, in this case we were able to make use of a separate study, which will be published elsewhere, of a color-magnitude diagram (CMD) derived from the F430W and F480LP images. The blue star is invisible on the F480LP image but was measured easily with the DAOPHOT photometry package on the F430W image. DAOPHOT allows recovery of the counts that correspond to its magnitude scale, since its final PSF-fitted magnitudes have a zero point that can be related to the earlier stage of aperture photometry. The result was that the star has 2312 counts within a radius of 3 pixels. Again deriving a growth curve from a Tiny Tim PSF, we found that the total counts are 20,104, or 5.50 per second, corresponding in this band to an F_λ of 1.80 × 10^{-16} ergs cm^{-2} s^{-1} Å^{-1}.

The second method involves deriving a *B*-magnitude for the star. The CMD referred to has a well-defined horizontal-branch stub, which could be compared with that in the CMD

TABLE 1

POSITIONS (EPOCH 1950)

Object	α	δ	Reference
X-ray source	18ʰ20ᵐ27.ˢ84 ± 0.″9	−30°23′17.″0 ± 0.″9	Grindlay et al. 1984
VLA position	18 20 27.719 ± 0.ˢ006	−30 23 15.80 ± 0.″08	Johnston & Kulkarni 1992
Optical position	18 20 27.81 ± 0.″2	−30 23 15.7 ± 0.″2	This *Letter*
Cluster center	18 20 27.80 ± 0.″2	−30 23 16.3 ± 0.″2	This *Letter*

of Liller & Carney (1978) to give a correct zero point for the magnitudes and colors. (The comparison included a correction for the quite appreciable color equation of F430W with respect to *B*, which we had calculated by means of synthetic photometry.) The *B* magnitude of the star came out to be 18.7. From Allen (1973) it can be calculated that the magnitude $B = 0$ corresponds to a flux of 6.61×10^{-9} ergs cm^{-2} s^{-1} $Å^{-1}$ at 4400 Å. The magnitude $B = 18.7$ then corresponds to 2.19×10^{-16} ergs cm^{-2} s^{-1} $Å^{-1}$.

When wavelength differences are also allowed for, these two blue flux estimates differ by about 50%. We can see no better course than to average them. Giving somewhat higher weight to the magnitude-based calculation results in a compromise flux value of 2.0×10^{-16} ergs cm^{-2} s^{-1} $Å^{-1}$, at 4300 Å. This value has to be considered uncertain by about 30%.

The above fluxes are observed values, uncorrected for interstellar extinction. For this correction we follow Rich, Minniti, & Liebert (1993), who take $E(B-V) = 0.25$ mag for NGC 6624 and use the extinction curve of Savage & Mathis (1979). The extinction values that we find are 2.12 mag at 1400 Å and 1.04 mag at 4300 Å, so that the corrected fluxes are 1.8×10^{-14} and 5.2×10^{-16} ergs cm^{-2} s^{-1} $Å^{-1}$, respectively.

Our 1400 Å flux is in good agreement with that in the *IUE* spectrum of Rich et al. (1993, their Fig. 3), where we derive by interpolation at 1400 Å 2.2×10^{-14} ergs cm^{-2} s^{-1} $Å^{-1}$.

The ratio of the two fluxes is 35, while the fourth power of the ratio of the wavelengths is 89. The spectral slope is not far from Rayleigh-Jeans. If expressed as a power of the wavelength, the decline from 1400 to 4300 Å goes as $\lambda^{-3.2}$. The gentler dropoff might suggest that the source of the radiation is not quite hot enough to descend with the severity of the Rayleigh-Jeans law.

7. INTERPRETATION

In choosing a reddening of 0.25 mag for NGC 6624, Rich et al. (1993) found an apparent distance modulus of 14.40 for the cluster (their Table 2), corresponding to a distance of 7.6 kpc. The spectrum of the X-ray source has been observed to fit well to an optically thin bremsstrahlung spectrum characterized by a temperature of 13 keV, or about 1.5×10^8 K (Stella, Kahn, & Grindlay 1984). The effective temperature, calculated from the total luminosity and the assumed size of the neutron star, is about 1.9×10^7 K. At optical wavelengths the emitter is more likely to be optically thick, however. It is easy to calculate that a blackbody at this effective temperature, with a radius of 5–10 km, would from that distance yield a flux at 1400 Å that is only a few millionths of what we observe. What is much more likely is that the radiation comes from an accretion disk of more moderate temperature but much larger area, or else from the intense illumination of the companion by the neutron star. For further discussion of this question, see the accompanying paper by Arons & King (1993).

(The distance used by Stella et al. is not the same as that used by Rich et al., but this small difference has no effect on the reasoning just given.)

Another important problem is the negative $\dot{P}$ of the binary orbit, which goes against the usual evolutionary interpretation and suggests a gravitational acceleration. When the object was thought to be 3″–4″ from the cluster center, this seemed unlikely (van der Klis et al. 1993); but now that the object turns out to be less than an arcsec from the center, the discussion given by van der Klis et al. indicates that the gravitational interpretation now becomes somewhat more plausible.

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