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EVIDENCE FOR EXTENDED X-RAY EMISSION FROM GLOBULAR CLUSTERS

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ABSTRACT

Deep exposures with the *Einstein Observatory* show evidence for diffuse X-ray emission from three globular clusters. One possible interpretation of these observations is that we are observing the interaction between a cluster wind and a hot gaseous galactic halo. The one cluster for which the proper motion has been measured is consistent with this interpretation.

Subject headings: clusters: globular — stars: mass loss — X-rays: general

I. INTRODUCTION

Current ideas concerning the evolution of globular cluster stars suggest that appreciable mass ($\sim 0.2\ M_\odot$) is lost from each star as it evolves from the main sequence to the horizontal branch phase. In fact, high dispersion spectroscopic observations of giant stars in three globular clusters by Cohen (1976) do show evidence that such mass loss is taking place. In view of this, it is somewhat surprising that numerous careful searches have failed to detect any *diffuse* gas in globular clusters. (e.g., Hills and Klein 1973; Knapp, Rose, and Kerr 1973; Faulkner and Freeman 1977; Hesser and Shawl 1977; Troland, Hesser, and Heiles 1978; Bowers *et al.* 1979). An obvious solution to this dilemma is that the gas is being removed continuously from the clusters. Two possible removal mechanisms are clusters winds (Burke 1968; Rose and Scott 1975; Vanden Berg 1978) or ram pressure stripping by interstellar (halo) gas (Frank and Gisler 1976). Both of these mechanisms would be expected to give rise to gas temperatures $\sim 10^5$ K and thus make the globular clusters candidates for the detection of soft X-ray emission.

This *Letter* is a report on an observational search for diffuse X-ray emission from three globular clusters: 47 Tuc, ω Cen, and M22, using the *Einstein Observatory*.

II. OBSERVATIONS

The above clusters were chosen for observation because they are among the intrinsically most luminous and hence among those most likely to retain gas lost during stellar evolution. Positional information for the three clusters is given in Table 1. The observations were made with the Imaging Proportional Counter (IPC) of the *Einstein Observatory* with exposure times of $\sim$ 22,000 s for 47 Tuc and ω Cen, and $\sim$ 24,000 s for M22. The clusters were purposely offset 10′ from the center of the IPC field to avoid confusion between a possible slow radial gradient in any observed X-ray emission and the instrumental sensitivity.

The standard reduction package for IPC data found a number of point sources in each of the cluster fields, as well as the obvious strong extended source $\sim$ 10′ NW of the center of M22. However, since this standard reduction is not particularly suited to detecting faint, extended sources (a mean background is subtracted from the whole field, so that the source itself may be taken as the background), we reprocessed the data using two different methods of background subtraction. First, a mean background count was obtained at approximately the same radial distance from the center of the field as the cluster. We were careful to choose a region where there was not an obvious point source or a significant part of the extended cluster source. This background was then subtracted, using an *Einstein* reduction program which properly accounts for the vignetting across the field. Contour diagrams were constructed from the resulting image. Second, a relatively empty, long-exposure ($\sim$ 54,000 s), deep survey field obtained in the course of another program was provided by C. and W. Forman. This field was reoriented for each of our clusters, renormalized, and then subtracted from our cluster fields. This second method of background subtraction is, in theory, superior to the first because it automatically

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TABLE 1

POSITIONAL DATA FOR THE OBSERVED GLOBULAR CLUSTERS

Cluster	l	b	Adopted Distance (kpc)	Z (kpc)
47 Tuc	306°	−45°	3.9	2.8
ω Cen......	309	+15	6.0	1.6
M22.......	9	−8	3.2	0.44

compensates for nonuniformities in background and detector sensitivity. However, the "blank" field was not completely blank but had several weak sources within it, so while it gave satisfactory background removal, it also created a few "holes" in the data. The important point is that the resulting contour diagrams from both techniques were very similar, differing only in small details. This shows that, within the region enclosed by the detector ribs, the program accounts well for changes in the instrumental sensitivity. Because all of the contours are positive using the first method of background subtraction, we have chosen to show those in Figures 1, 2, and 3 (Plates L1, L2, and L3). The contours are expressed in terms of the number of sigma above the background and are shown superposed on reproductions of the Science Research Council (SRC) southern survey. The contours are the result of a four-point convolution; i.e., they are smoothed with a 32″ Gaussian. The total number of IPC counts, after background removal, for various sized regions are given in Table 2.

All of the fields appear to contain both extended and point sources. Some of the point sources can easily be identified with foreground stars. (See, e.g., those stars pointed out in the caption of Fig. 1.) Others, such as two point sources ~ 5′ north of the center of ω Cen, could be background objects, such as QSOs. A preliminary search to optically identify the noncentral point sources was done by photographic *UBV* photometry of stars in the vicinity of the point sources. In addition, several stars were observed spectroscopically. No obvious optical counterparts were found, but a more thorough search will be carried out in the future.

Earlier High Resolution Imager (HRI) observations show that the strongest part of the central source in 47 Tuc is pointlike (Grindlay 1981). Both M22 and ω Cen may also contain central point sources which are weaker than the 47 Tuc source and therefore were not detected in earlier surveys. Because such a central point source in M22 or ω Cen would be comparable in luminosity to the surrounding diffuse source, it is more difficult to isolate it with the lower spatial resolution of the IPC. Our observations are not inconsistent with a weak point source being present near the centers of both of these clusters.

In addition to the point sources discussed above, all three clusters appear to contain an extended source of X-ray emission near the cluster center. In all cases this emission is not symmetrical about the center but lies well within the tidal radius, which is typically larger than the region pictured in Figures 1–3. The fluxes and luminosities of these sources, within specified areas, are given in Table 2. From the compilation of Vaiana *et al.* (1981), we note that these integrated luminosities are similar to those observed for O and B stars, but not for the late-type giants known to be present in these clusters.

III. DISCUSSION

In the absence of any obvious stellar counterparts to our cluster sources, we consider the possibility that we may be observing X-rays from a hot diffuse gas. If we are observing a cluster wind, we would predict that X-rays would be observed both from (a) a bright, central core source and (b) a bow shock, if the cluster is moving through a hot, gaseous medium (cf. calculations by Lea and De Young 1976). The observations presented here are consistent with the presence of a central source and a bow shock. Direct observational evidence for a hot galactic halo, through which these clusters would be moving, now exists (Savage and de Boer 1979; Ulrich *et al.* 1980). We can test whether our observations are consistent with the existing wind models for clusters.

First, some constraints on particle densities and temperatures can be imposed by the observed luminosities

TABLE 2

FLUXES AND LUMINOSITIES FOR CLUSTER SOURCES (0.5–3.5 keV)

Object	Region	Size (width × height)	No. IPC Counts	Flux (ergs cm^{-2} s^{-1})	Luminosity (ergs s^{-1})
47 Tuc ...	Central	7′ × 7′	394	4.4×10^{-13}	7.7×10^{32}
	Whole cluster	14 × 22	852	9.6×10^{-13}	1.6×10^{33}
ω Cen	Central	18 × 11	594	6.6×10^{-13}	2.7×10^{33}
	Whole cluster	28 × 23	1216	1.3×10^{-12}	5.3×10^{33}
M22	Central	7 × 6	271	2.8×10^{-13}	3.2×10^{32}
	Whole cluster	26 × 24	2718	2.8×10^{-12}	3.2×10^{33}
	NW source	8 × 7	554	5.7×10^{-13}	6.4×10^{32}

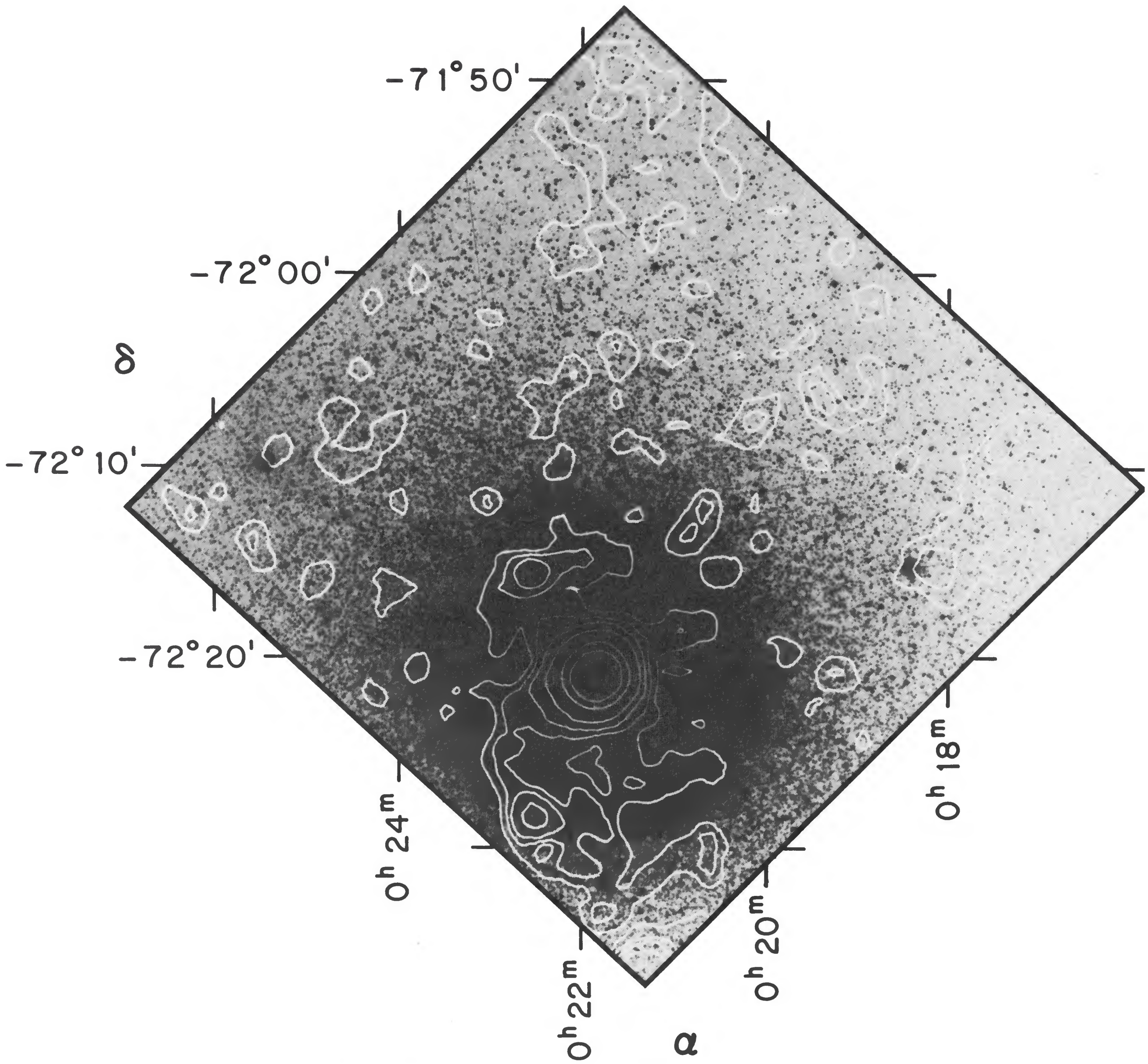

FIG. 1.—Globular cluster 47 Tuc (NGC 104) from blue SRC photograph with X-ray contours superposed. The contours are significance levels above the background of $\sigma = 1.5, 3, 5, 9, 20$, and 30. All photographs have been trimmed so that the detector ribs lie just outside the region shown. Some bright foreground stars apparently are weakly detected in X-rays: HD 1701 ($\alpha = 0^h18^m$, $\delta = -72°16'$, K0 IV), HD 2041 ($\alpha = 0^h22^m$, $\delta = -72°32'$, F6 IV–V), and HD 2466 ($\alpha = 0^h25^m$, $\delta = -72°10'$, F8 IV–V). Spectral types are from Houk and Cowley (1975).

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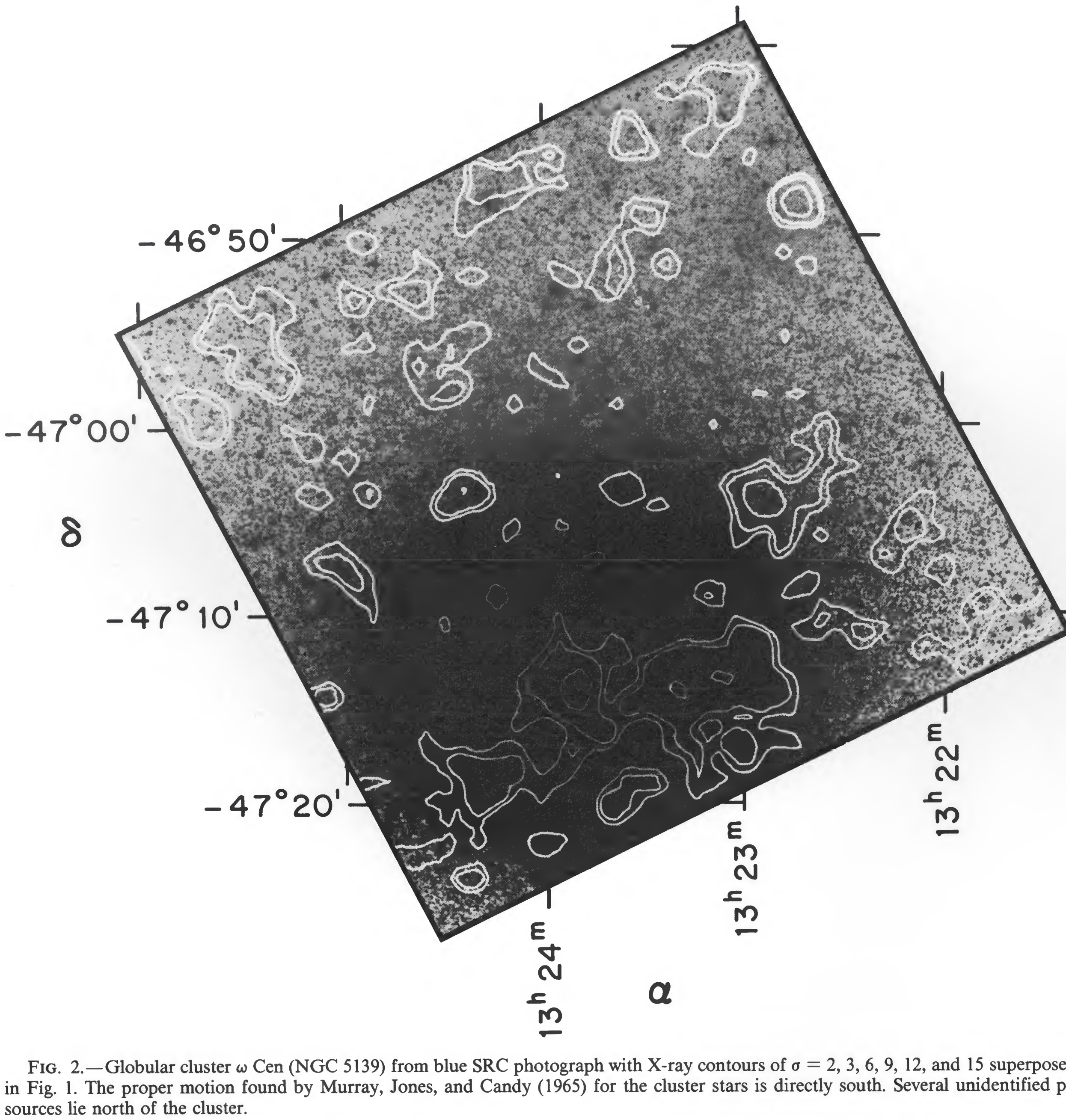

FIG. 2.—Globular cluster ω Cen (NGC 5139) from blue SRC photograph with X-ray contours of $\sigma = 2, 3, 6, 9, 12$, and 15 superposed as in Fig. 1. The proper motion found by Murray, Jones, and Candy (1965) for the cluster stars is directly south. Several unidentified point sources lie north of the cluster.

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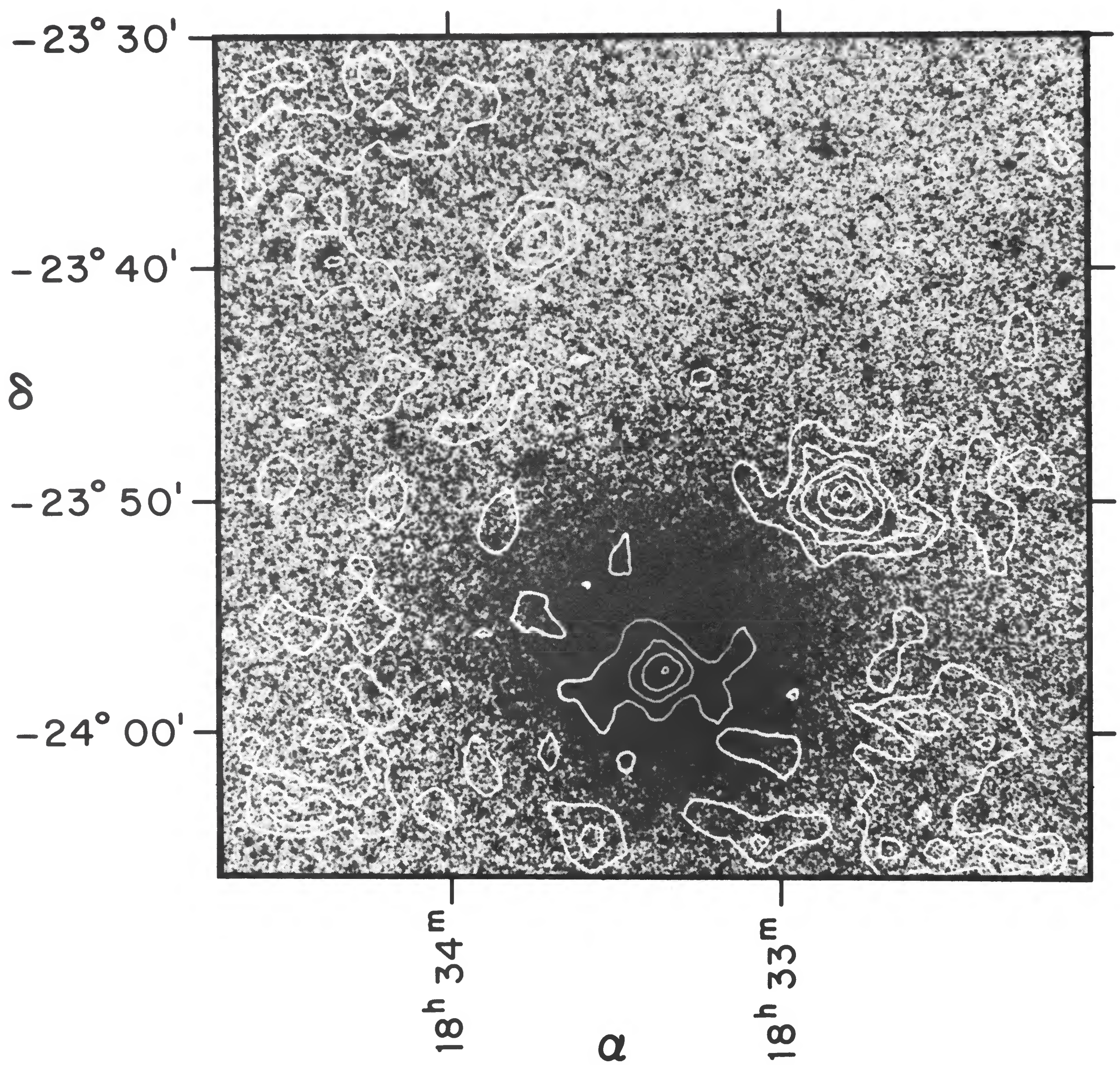

FIG. 3.—Globular cluster M22 (NGC 6656) from blue SRC photograph with X-ray contours of $\sigma = 3, 5, 7, 9$, and 11 superposed as in Fig. 1. Note the extended, soft X-ray source to the northwest of the cluster (centered at $\alpha = 18^h33^m$, $\delta = -23°50'$). Its X-ray intensity is greater than the central cluster source (see Table 2), and its X-ray spectrum is considerably softer than the central source. Although it lies well within the tidal radius of the cluster, it is unclear whether it belongs to the cluster. At lower contour levels than those pictured, this NW source is connected to the central source, suggesting a common origin. The bright star at $\alpha = 18^h34^m$, $\delta = -23°40'$ (HD 171737, B9) is apparently a weak X-ray source.

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TABLE 3

PROPERTIES OF HOT GAS WITH IPC LUMINOSITY OF 5×10^{32} ergs s^{-1}

T (K)	n^2V (cm^{-3})	n[a] (cm^{-3})
10^5	1.2×10^{62}	206
3×10^5	3.1×10^{58}	3.3
10^6	1.1×10^{57}	0.6

[a]For $V = 2.9 \times 10^{57}$ cm^3.

of the central regions. In Table 3 we list, for different temperatures, the values of n^2V required to produce an *Einstein* IPC luminosity of 5×10^{32} ergs s^{-1}. For a representative volume (V) of 2.9×10^{57} cm^3 (the volume of a shell ~ 7 pc in radius and 0.7 pc thick which subtends π steradians at the cluster center), the required particle densities (n) are also tabulated. By comparing the numbers in the table with those derived from the time-independent models of Faulkner and Freeman (1977), we note that only the highest temperatures, and hence the highest injection energy models, come close to accounting for the central part of the extended X-ray sources as being due to cluster winds. (A "typical" core volume would be an order of magnitude less than the V assumed above.)

Similarly, if we were to postulate that the off-center "extended" sources were a bow shock caused by the interaction of the cluster wind with a hot galactic halo ($T \sim 10^{5-6}$, $n \sim 10^{-3}$ cm^{-3}), then wind densities an order of magnitude higher than those assumed by Faulkner and Freeman would be required to make the shock front occur as far from the center of the cluster as is observed. Furthermore, large compression factors ($\sim$ 100s) are required to produce the observed luminosities in the hypothesized bow shocks. However, such a large compression can occur in isothermal shocks (Spitzer 1978), but the cooling times for the gas at the temperatures and densities of Table 3 are sufficiently long so that it would seem unlikely that the shock would be isothermal. Further model computations, such as those of Lea and De Young (1976), are needed to clarify this discussion.

In summary, the observations of both the intensity of the core and the extent of the "bow shock" are higher than predicted from existing wind models for clusters, but they could be understood if the assumed wind densities were higher.

We conclude by noting one additional small but tantalizing piece of evidence suggestive of the bow shock hypothesis. In the analysis of the proper motions of stars in ω Cen, Murray, Jones, and Candy (1965) find a southerly tangential motion for this cluster which is consistent with the morphology of the observed X-ray source.

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REFERENCES

Bowers, P. F., Kerr, F. I., Knapp, G. R., Gallagher, J. S., and Hunter, D. A. 1979, *Ap. J.*, **233**, 553.
Burke, J. A. 1968, *M.N.R.A.S.*, **130**, 241.
Cohen, J. G. 1976, *Ap. J. (Letters)*, **203**, L127.
Faulkner, D. J., and Freeman, K. C. 1977, *Ap. J.*, **211**, 77.
Frank, J., and Gisler, G. 1976, *M.N.R.A.S.*, **176**, 533.
Grindlay, J. E. 1981, *X-Ray Astronomy with the Einstein Satellite*, ed. R. Giacconi (Dordrecht: Reidel), p. 79.
Hesser, J. E., and Shawl, S. J. 1977, *Ap. J. (Letters)*, **217**, L143.
Hills, J. G., and Klein, M. J. 1973, *Ap. Letters*, **13**, 65.
Houk, N., and Cowley, A. P. 1975, *University of Michigan Catalogue of Spectral Types*, Vol. **1** (Ann Arbor: Astronomy Department, University of Michigan).
Knapp, G. R., Rose, W. R., and Kerr, F. J. 1973, *Ap. J.*, **186**, 831.
Lea, S. M., and De Young, D. S. 1976, *Ap. J.*, **210**, 647.
Murray, C. A., Jones, D. H. P., and Candy, M. P. 1965, *Royal Obs. Bull.*, No. 100.
Rose, W. K., and Scott, E. H. 1975, *Ap. J.*, **197**, 147.
Savage, B. D., and de Boer, K. S. 1979, *Ap. J. (Letters)*, **250**, L77.
Spitzer, L. 1978, in *Physical Processes in the Interstellar Medium* (New York: Wiley), p. 221.
Troland, T. H., Hesser, J. E., and Heiles, C. E. 1978, *Ap. J.*, **219**, 873.
Ulrich, M. H., *et al.* 1980, *M.N.R.A.S.*, **192**, 561.
Vaiana, G. S., *et al.* 1981, *Ap. J.*, **245**, 163.
Vanden Berg, D. A. 1978, *Ap. J.*, **224**, 394.

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