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Study of Diffuse X-ray Emission in Globular Clusters
Final Report (6/15/91 - 12/14/97)

submitted by:

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1 Introduction

This grant supported our analysis of ROSAT x-ray data on globular clusters. Although the grant title referred to our original ROSAT proposal (cycle 1) to study diffuse soft x-ray emission in three globulars (for which time was only granted in that original observing cycle for one cluster, 47 Tuc), the grant has also been maintained through several renewals and funding supplements to support our later ROSAT observations of point sources in globulars. The primary emphasis has been on the study of the dim sources, or low liuminosity globular cluster x-ray sources, which we had originally discovered with the Einstein Observatory and for which ROSAT provided the logical followup.

In this Final Report, we summarize the Scientific Objectives of this investigation of both diffuse emission and dim sources in globular clusters and the Results Achieved; and finally the Papers Published.

2 Scientific Objectives of the Research

Our objectives in the study of globular cluster x-ray emission divided, naturally, into two broad categories: studies of the diffuse emission and studies of the dim source population. Together these objectives allowed even more fundamental objectives for the study of globular clusters to be addressed. Below we describe these three separate objectives in turn.

1. *Diffuse X-ray Emission in Globulars:* Our initial objective was to detect and study the diffuse soft x-ray emission originally reported by us (Hartwick, Cowley and Grindlay 1982, ApJ, 254, L11) in three globulars: 47 Tuc, ω-Cen, and M22. The Einstein detections were marginal but had provided the first evidence for the long-sought bow shock emission from gas in globular clusters encountering the halo at the cluster velocity of $\sim$150 km/s.

2. *Low Luminosity X-ray Sources in Globulars:* This program has had as its principal objective the study of the dim, or low luminosity, x-ray sources in globulars. These sources were also discovered originally with Einstein observations (Hertz and Grindlay 1983, ApJ,275,105) and have been the subject of major interest ever since as they may provide the best evidence for the long-sourght population of accreting white dwarfs (i.e. cataclysmic variables). Alternatively, the more luminous members of this class of dim sources undoubtedly contain an admixture of quiescent low mass x-ray binaries containing neutron star primaries. Sorting out the CV vs. qLMXB population has been a major challenge.

3. *Fundamental Constraints on Stellar and Dynamical Evolution in Globulars:* By eventually understanding the relative CV vs. qLMXB populations, we hope to constrain the initial mass function in globular clusters. The relative production of white dwarfs (WDs) vs. neutron stars (NSs) can in principle be measured by the CV vs. qLMXB populations in the dim x-ray sources, and thus constrain the cluster IMF which would (for example) favor NS production for a flat IMF and high mass cutoff. Binary production and thus the cluster dynamical evolution (which is driven by binaries) can in principle be constrained by the relative population of CVs vs. isolated WDs.

3 Results Achieved

Although our study of globular cluster x-ray sources is very much continuing, this ROSAT grant has allowed considerable progress to be made. Below we list the highlights for each of the principal scientific objectives.

Diffuse Emission:
We have detected diffuse x-ray emission in 47 Tuc, though with different morphology than originally suspected from the Einstein observations. Detailed results are reported in Krockenberger and Grindlay (1995=KG). In brief, we found convincing evidence for the bow shock in 47 Tuc as an enhanced region of soft emission (estimated temparature: $\sim 1 \times 10^6$ K) on the NE side of the cluster, with radial offset $\sim$6 arcmin and angular size $\sim$2 arcmin. The emission may trail around either side of the cluster (similar to a tailed radio galaxy morphology), which lends further support to the interpretation that it is due to gas expelled from mass loss of cluster giants being shock heated by the cluster motion through the galactic halo. The direction of the cluster velocity vector with respect to the halo gas (when corrected for modest halo rotation) agrees with the position angle of the diffuse emision.

The broad diffuse emission on the leading edge of the cluster is itself sub-divided into two regions of harder diffuse emission (denoted sources A and B in KG). Since these appear to straddle the bowshock, we interpret them as non-thermal emission from mildly relativistic electrons accelerated in the shock that are inverse Compton scattering cluster starlight. A much deeper AXAF observation is planned to followup on this discovery.

We have also found evidence for diffuse emission on the northern side of NGC 6752. This may be a similar bowshock type emission as in 47 Tuc. Results are currently being incorporated into our paper on low luminosity sources in NGC 6752 (Grindlay et al 1998a).

Low Luminosity Sources:
Certainly our major results have been for the discovery of multiple low luminosity sources in several clusters. In fact, all three clusters with high central densities observed by us (NGC 6397, NGC 6752, 47 Tuc) contain multiple low luminosity ($\lesssim 10^{33}$ erg/s) sources. We have by far devoted the most effort to our study of NGC 6397, with preliminary results reported by Grindlay (1993) and Cool et al (1993). In the initial 20 ksec observations, at least 3 sources (C1-C3) were detected in the central 10 arcsec radius core region of the cluster, with two additional sources (B and A) farther out. These results led to our successful HST observations of this cluster with a narrow-band (Hα) imaging study which identified emission line candidates in the ROSAT error boxes. Our followup spectroscopy program confirmed that these are almost certainly the long-sought population of CVs. We are currently finishing the analysis of the followup deep (75ksec) ROSAT observations of NGC 6397 which have detected an even more complex source distribution in the core: at least 2-3 additional, fainter sources are found, and source varibility is evident over the 2 week span of the observation. This study has, again, motivated a planned followup still deeper, and higher resolution, AXAF study of this prototypical post core collapse cluster.

Similarly, our preliminary results for NGC 6752 in which at least two sources were detected within the 30 arcsec core region led to our likely HST identification of one with a CV (Bailyn et al 1996). Final results on this cluster, including the diffuse emission, are nearing completion (Grindlay et al 1998a). For ω-Cen, we found (Cool et al 1995) that two of the original Einstein sources are in fact foreground dMe stars. However, at least one and possibly two additional low luminosity sources not resolved with Einstein were detected in the central core. Finally, the other clusters observed in our various ROSAT observations (M22 and M71) are included in a compendium paper now nearing completion (Cool et al 1998).

General Results:
This program has led to numerous general results for the nature and origin/evolution of compact objects and binaries in globulars as well as some constraints on globular clusters and the Galaxy:

- hot gas from a cluster bow shock has finally been detected, confirming the expectation that clusters do contain a low density ISM from the accumulated mass loss from their AGB stars (KG).

- the bow shock implies the halo of the Galaxy is rotating at nearly the underlying disk velocity and that the halo is at an intermediate temperature $\sim 10^5$ K (KG).
- the first CVs have been detected initially in x-rays and identified optically with HST for a globular cluster (Grindlay 1993, Cool et al 1993, Grindlay et al 1995, Grindlay 1995, 1996).
- the cluster CVs may be dominated by magnetic CVs, given their optical spectra. X-ray spectra (with AXAF) may be able to confirm this (Grindlay et al 1995, Grindlay 1996).
- the cluster CV population in NGC 6397 vs. 47 Tuc may constrain the WD vs. NS population in these two very different (metallicity) clusters (Grindlay 1994, 1995, 1996).

4 Papers Published

Following are papers on our study of x-ray bursters which report results achieved in this study:

1. "CVs in Globular Clusters: Clues to Compact Binary Production ", (J.E. Grindlay), in *X-ray Binaries and Recycled Pulsars*, (E.P.J. van den Heuvel and S.A. Rappaport, eds.), NATO ASI Series, volume 377, pages 365-374 (1992).
2. "Early Studies of Globular Clusters With ROSAT" (J.E. Grindlay), in *Structure and Dynamics of Globular Clusters*, (S. Djorgovski and G. Meylan, eds.), ASP Conference Series, Volume 50, pages 285-298 (1993).
3. "Discovery of Low Luminosity X-ray Sources in NGC 6397" (A. Cool, J. Grindlay, M. Krockenberger, and C. Bailyn), in *Structure and Dynamics of Globular Clusters*, (S. Djorgovski and G. Meylan, eds.), ASP Conference Series, Volume 50, pages 307-308 (1993).
4. "Optical, X-ray and Gamma-Ray Observations of Compact Objects in Globular Clusters" (J.E. Grindlay), *Advances in Space Research*, volume 13, No. 12, pages 597-609 (1993).
5. "X-raying Stellar Remnants in Globular Clusters" (J.E. Grindlay), in *The Globular Cluster-Galaxy Connection*, (G. H. Smith and J.P. Brodie, eds.), ASP Conference Series, Volume 48, pages 156-166 (1993).
6. "Discovery of Multiple Low Luminosity X-ray Sources in NGC 6397" (A.M. Cool, J.E. Grindlay, M. Krockenberger, and C.D. Bailyn), *Astrophysical Journal Letters*, volume 410, L103-L106 (1993).

7. "X-ray Binaries in Globular Clusters: Links to the Compact Binary Zoo" (J.E. Grindlay), *Memorie della Societa Astronomica Italiana* (Journal of the Italian Astronomical Society), volume 65, No. 1, pages 259-271 (1994).

8. "Dim X-ray Sources in Globular Clusters" (J.E. Grindlay), in *Evolution of X-ray Binaries*, (S. Holt and C. Day, eds.), AIP Conference Proceedings, volume 308, pages 339-350 (1994).

9. "The Faint X-ray Sources In and Out of ω-Centauri: X-ray Observations and Optical Identifications" (A.M. Cool, J.E. Grindlay, C.D. Bailyn, P.J. Callanan, and P. Hertz), *Astrophysical Journal*, volume 438, pages 719-723 (1995).

10. "Discovery of Candidate Cataclysmic Variables in the Post-Core Collapse Globular Cluster NGC 6397" (A.M. Cool, J.E. Grindlay, H.N. Cohn, P.M. Lugger and S.D. Slavin), *Astrophysical Journal*, volume 439, pages 695-704 (1995).

11. "Discovery of Diffuse X-ray Emission in 47 Tuc" (M. Krockenberger and J.E. Grindlay), *Astrophysical Journal*, volume 451, pages 200-209 (1995).

12. "X-ray Sources vs. Millisecond Pulsars in Globular Clusters" (J.E. Grindlay), in *Millisecond Pulsars: A Decade of Surprise*, (A. Fruchter, M. Tavani and D. Backer, eds.), ASP Conference Series, volume 72, pages 57-71 (1995).

13. "High Resolution Studies of Compact Binaries in Globular Clusters With HST and ROSAT" (Jonathan E. Grindlay) in *Dynamical Evolution of Star Clusters* (P. Hut and J. Makino, eds.), Proc. IAU Symp. 174 (Tokyo), Kluwer, pages 171-180 (1996).

14. "Hubble Space Telescope Observations of the Post-Core-Collapse Globular Cluster NGC 6752: A Search for Cataclysmic Variables" (C.D. Bailyn, E.P. Rubenstein, S.D. Slavin, H. Cohn, P.N. Lugger, A.M. Cool and J.E. Grindlay), *Astrophysical Journal Letters*, volume 473, pages L31- L34 (1996).

15. "Low Luminosity Sources in ω-Cen, M22 and M71", (A.C. Cool, C. Bailyn, J.E. Grindlay et al), *Astrophysical Journal*, in preparation (1998)

16. "Low Luminosity Sources in NGC 6752", (J.E. Grindlay, A.C. Cool, C. Bailyn, et al), *Astrophysical Journal*, in preparation (1998a)

17. "Deep ROSAT Study of the Low Luminosity Sources in NGC 6752", (J.E. Grindlay, A.C. Cool, C. Bailyn, et al), *Astrophysical Journal*, in preparation (1998b)