x-ray source. Yet, this huge amount of hot plasma may indicate intermittent activity in the galactic nucleus. There is other observational evidence for a large mass concentration at the galactic center, suggestive of a massive black hole. Observations with ASCA have also revealed x-ray luminous nuclei in several spiral galaxies like ours (the nucleus of M81 in Fig. 1 is an example), indicating an activity similar to that in AGNs even in normal galaxies. These nuclei are less luminous than the previously known AGNs and hence may be called "mini AGNs."

ASCA is the first x-ray observatory able to provide spatially resolved spectra of the hot gas in clusters of galaxies. The results of such studies are important as they have significant implications for the cosmological evolution and the problem of dark matter which determines the gravitational potential of clusters of galaxies. Investigations of clusters of galaxies with ASCA have just started, and we anticipate significant advances.

Finally, the origin of the intense cosmic x-ray background (CXB), whose existence has been known since the birth of x-ray astronomy, is an important but still unresolved issue. As the sensitivity of observations has improved, the CXB has been increasingly resolved into discrete sources. The ROSAT deep survey has resolved more than 70% of the CXB below 2 keV into discrete sources, of which the majority are found to be AGNs, but there remains the puzzling "spectral paradox": The CXB has a slope (the exponent of a power law) of –1.4 in the photon number spectrum, whereas most AGNs have softer spectra, with an average slope of –1.7. Known AGNs therefore cannot account for the entire CXB, and a significant fraction of the CXB must be due to galaxies with flatter (harder) spectrum in order to account for the CXB spectrum. Capable of determining the spectral shape with its wide-band coverage, ASCA will be able to find the yet unidentified contributors to the CXB.

References

1. R. Giacconi *et al.*, *Phys. Rev. Lett.* **9**, 439 (1962).
2. H. Tananbaum, *Astrophys. Space Sci. Libr.* **43**, 208 (1974).
3. T. Maccacaro *et al.*, *Astrophys. J.* **253**, 504 (1982); R. Mushotzky, C. Done, K. Pounds, *Annu. Rev. Astron. Astrophys.*, in press.
4. W. Forman and C. Jones, *Annu. Rev. Astron. Astrophys.* **20**, 547 (1982).
5. K. Makishima, in *The Structure and Evolution of Neutron Stars*, D. Pines, R. Tamagaki, S. Tsuruta, Eds. (Addison-Wesley, New York, 1992), p. 86.
6. Y Tanaka, in *Proceedings of the Ginga Memorial Symposium* (Institute of Space and Astronautical Science, Kanagawa, 1992), p. 19.
7. T Dotani *et al.*, *Nature* **330**, 230 (1987).
8. R Sunyaev *et al.*, *ibid.*, p. 227.
9. H. U. Zimmermann *et al.*, *IAU Circular No. 5748* (1993).
10. Y. Tanaka and the ASCA Team, *IAU Circular No. 5753* (1993).
11. K. Koyama, *Nature* **339**, 603 (1989).

The Case of the Blue Stragglers

Charles Bailyn

Globular star clusters, dense aggregations of up to a million stars, have long been a favorite target for observers. Seen through a modest telescope, they provide a spectacular visual display for amateur astronomers. For professionals, the opportunities provided by a homogeneous group of stars of the same age, distance, and chemical composition are no less enticing. Recent observations by the Hubble Space Telescope (HST) of the dense cores of globular clusters have revealed a variety of exotic stars, hotter and bluer than the typical cluster stars.

Globular clusters provide crucial observational tests of theories of stellar evolution. Theoretical models that predict the properties of a population of stars of uniform age, distance, and chemical composition can be compared with the observations. Such a comparison not only tests the stellar models, but also provides estimates for the physical parameters of the cluster as a whole. In addition, the clusters are almost perfect manifestations of the classic "gravitational N-body problem," in which one wishes to solve the equations of motion for a large collection of objects interacting solely through gravity.

The advent of large computers and efficient programs has led to great progress in the N-body problem (*1*). Numerical studies show that the density of stars at the core of a globular cluster increases with time, leading in principle to a central "cusp" of infinite density. Such an endpoint is clearly unphysical, and when the core density becomes high, close encounters between stars and binary star systems begin to radically alter the stellar velocity distribution. Energy can be added to the motions of stars in the core, halting core collapse in much the same way that the initiation of nuclear fusion prevents the collapse of the gas in the center of an individual star. These collisions and near collisions control the overall evolution of the cluster but may also do drastic damage to individual stars and may provide an explanation for the existence of certain stars whose presence in globular clusters has long baffled students of stellar evolution.

It is almost impossible to observe individual stars in globular cluster cores from ground-based telescopes. The Earth's atmosphere blurs the stellar images, combining the light from hundreds of stars into a single fuzzy blob. The HST was expected to revolutionize studies of cluster cores by resolving the fuzzy blurs into hundreds of individual points, but the problem with the HST primary mirror set back these hopes; the malformed mirror spreads the light from a single star over a large area, just as the atmosphere does. But there is a crucial difference between images blurred by the atmosphere and those blurred by the HST mirror. The HST images concentrate about 15% of the starlight into a central "spike" of light. By studying this central spike and ignoring the remaining 85% of the light, astronomers have been able to distinguish the individual stars in the centers of several globular clusters despite the HST's optical flaw.

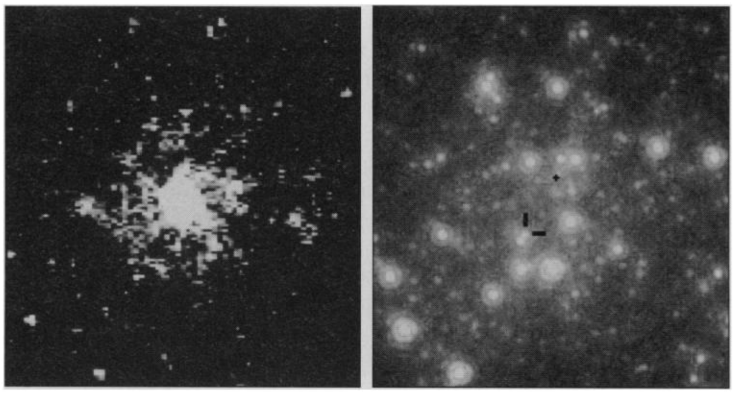
There are limitations to what can be done with HST. Accurate measurements of the brightness of the stars are impossible because the fraction of light in the central spike varies with time, the position of the star within the image, and the wavelength of the light in ways that are difficult to calibrate. Exposure times have to be increased because only 15% of the light is being used: Faint stars are often lost in the blur from their brighter neighbors and cannot be measured at all. Nevertheless, the positions and approximate fluxes of stars in crowded cluster cores can be determined with HST far better than has ever been done from the ground.

The advantages of HST are particularly acute for blue stars because it can observe ultraviolet (UV) photons, which are blocked by the Earth's atmosphere. In the UV, blue stars stand out against the background of generally red globular-cluster stars, which obliterate them in images at optical wavelengths. Standard models of stellar evolution predict that there should be no blue stars in globular clusters; as in all old stellar systems, the blue (brighter and more massive) stars should long ago have evolved through the red giant stage and then died. The only blue stars expected in globular clusters are exotic objects created by stellar collisions and interactions. The HST is therefore particularly well suited to identify stars that have undergone such cataclysms. In particular, HST has broken new ground in the study of two kinds of blue cluster stars: blue stragglers and x-ray–emitting binary systems.

Blue stragglers have been a thorn in the side of students of stellar evolution since

The author is in the Department of Astronomy, Yale University, New Haven, CT 06511.

their discovery 40 years ago. The brightness and color of these stars suggests that they are normal "main sequence" stars like the sun, powered by hydrogen fusion, but they are brighter and bluer than other main sequence stars in the clusters to which they belong, implying that they should long since have used up all the nuclear fuel in their cores and evolved away from the main sequence. Blue stragglers appear to be much younger than their neighbors, but this is unlikely because clusters contain no gas or dust out of which new stars could form. Another explanation for the stragglers is that some mechanism has mixed hydrogen from their surfaces down into their cores, prolonging their main sequence lifetimes, but no plausible mixing mechanism has been proposed. Current thinking favors a third alternative, namely stellar mergers. In the dense environment of a globular cluster, two stars that have spent most of their lives as slowly evolving low-mass stars can collide and merge to form a blue straggler. Alternatively, stars born as members of a binary star system might spiral together and merge.



A cluster's core. Two views of the globular cluster NGC 6624 in the constellation Sagittarius taken by the Faint Object Camera on the HST. When imaged in ultraviolet light (left), one star outshines its neighbors, whereas in blue light (right), the same star appears as a faint counterpart (identified by black lines) to the x-ray source 4U 1820-30. [I. King, University of California, Berkeley; and National Aeronautics and Space Administration–European Space Agency]

Ground-based observations of low-density globular clusters have shown that some of the blue stragglers they contain are binary stars, confirming the merger idea, but only for low-density clusters in which collisions should be rare (*2*). Before HST, blue stragglers could not be observed in the dense cores of globular clusters, where most collisions should take place. One of the first triumphs of HST was the discovery in 1991 of 21 blue stragglers in the core of the nearby dense cluster 47 Tucanae (*3*). This is a much studied cluster, but no blue stragglers had been seen from the ground, apparently because their large masses cause them to sink to the center of the cluster. The UV HST images of the cluster center showed the stragglers clearly and confirmed that at wavelengths near 2000 Å, they are the brightest stars in the cluster.

Recently M15, one of the densest clusters known, was found to contain blue stragglers at its core (*4*). The core of M15 contains a plethora of unusual objects, so the discovery of blue stragglers was not unexpected, but the studies also turned up a new and wholly unexpected population of stars the same color as ordinary main-sequence stars but several times brighter (*4, 5*). Astronomers have only begun to speculate about the origins of these stars, which have been dubbed "yellow stragglers." Further observations of M15 and the handful of equally dense clusters will be needed to confirm and extend the current results.

Twenty years ago, it became clear that there were proportionally more bright x-ray sources in globular clusters than elsewhere in the galaxy, and it was natural to assume that high stellar densities were somehow associated with their genesis. Certain kinds of binary star systems are well known as galactic x-ray sources and were plausible candidates for the x-ray emission from clusters. The currently accepted scenario involves a superdense neutron star passing within a few stellar radii of an ordinary star. Tidal oscillations induced in the normal star drain energy from the relative motion of the two stars, transforming an initially unbound orbit into a bound binary system. As the binary system evolves, mass is dragged from the ordinary star onto the surface of the neutron star, becoming hot enough to produce the enormous x-ray fluxes observed.

As increasingly detailed x-ray observations and theoretical models were made, it became urgent to identify the optical or UV counterparts of the x-ray sources. Outside of globular clusters, searches were made with some success, but years of effort had produced only one strong and one tentative candidate for the optical counterpart of an x-ray source in a globular cluster (*6, 7*). Observations with HST have now dramatically confirmed the tentative identification (*8*). Even more spectacularly, HST has at last revealed the optical counterpart of the x-ray source in the center of the cluster NGC 6624 (*9*) (see figure). This binary system contains a neutron star and a white dwarf star in the shortest orbit known, with a period of only 11 min. The luminosity of this source is 10,000 times that of the sun and is mostly in the form of x-rays emitted from a volume smaller than the Earth-moon system. Already, the HST data is being used to help model the remarkable physics of this binary star system (*10*).

The HST observations are also beginning to pin down the mysterious low-luminosity globular-cluster x-ray sources. These systems emit thousands of times fewer x-rays than the brighter sources and are generally thought to be binary stars in which a white dwarf is accreting matter from a companion. Such binary stars are well known outside of globular clusters and, by analogy with the brighter sources, were expected to appear in great numbers in globular clusters. But before HST, there was no observational evidence linking the faint cluster x-ray sources with accreting white dwarf systems and precious little evidence for the existence of any such stars in globular clusters at all. The HST observations of 47 Tucanae identified one such object (*11*). More recent HST observations of the x-ray emitting region of the globular cluster NGC 6397 have revealed objects with the blue color, faint luminosity, and strong Balmer emission lines, which are expected from accreting white dwarfs (*12*). Detailed spectroscopy with the refurbished HST should reveal whether these objects are indeed the long sought for population of accreting white dwarfs.

The HST discoveries to date are merely a prelude to what can be done if the mirror problems can be successfully resolved. The improved spatial resolution would enable far more precise observations to be performed on much fainter objects. If the mirror fix does indeed occur, the few years astronomers have spent working with a partially successful HST may prove to be a blessing in disguise. For with the insight gained from our taste of the potential of HST, we may be better equipped to digest the long-awaited feast.

References

1. S. G. Djorgovski and G. Meylan, Eds. *Structure and Dynamics of Globular Clusters* (Astron. Soc. Pac. Conf. Ser. 50, Astronomical Society of the Pacific, San Francisco, CA, 1993).
2. M. Mateo *et al.*, *Astron. J.* **100**, 469 (1990).
3. F. Paresce *et al.*, *Nature* **352**, 297 (1991).
4. G. de Marchi and F. Paresce, *Astrophys. J.*, in press.
5. P. B. Stetson, in preparation.
6. M. Auriere, O. Le Fevre, A. Terzan, *Astron. Astrophys.* **128**, 415 (1984).
7. J.-L. Nieto *et al.*, *ibid.* **239**, 155 (1990).
8. S. F. Anderson *et al.*, *Astron. J.* **106**, 1049 (1993).
9. I. R. King *et al.*, *Astrophys. J.* **413**, L117 (1993).
10. J. Arons and I. R. King, *ibid.*, p. L121.
11. F. Paresce *et al.*, *Nature* **360**, 46 (1992).
12. A. N. Cool, thesis, Harvard University (1993).