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NGC 5694: A GLOBULAR CLUSTER ESCAPING FROM THE GALAXY?

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A redetermination of the radial velocity and distance of the globular cluster NGC 5694 reveals that with respect to the galactic center it lies at $r = 26 \pm 5$ kpc with a velocity of $v_{cl} \lesssim -273 \pm 19$ km s^{-1}. The escape velocity at the location of the cluster is $v_{esc} = 190 \pm 35$ km s^{-1} for a conventional mass model of the Galaxy, which would indicate that NGC 5694 is indeed in a hyperbolic orbit. Alternatively, assuming the cluster to be in a bound orbit would require the galactic halo within $r \sim 25$ kpc to contain a mass $\gtrsim 0.8 \times 10^{11}\ \mathfrak{M}_\odot$, comparable with that of the disk.

Key words: globular clusters — radial velocities — galactic structure

The distant globular cluster NGC 5694 ($\alpha = 14^h36^m.7$, $\delta = -26°19'$ (1950); $\ell = 332°$, $b = +30°$) has been recognized for many years as an object which may not be gravitationally bound to the Galaxy. Earlier discussions (von Hoerner 1955; Kinman 1959*b*; Sandage and Wildey 1967) demonstrated that virtually all the known globular clusters could consistently be assumed to have bound orbits; by far the single most outstanding exception was NGC 5694, which from the older data appeared to be almost necessarily in a hyperbolic orbit.

Determination of its orbital status rests on two measured quantities, its radial velocity and distance from the galactic center. As was indicated by Kinman (1959*b*), the previous analyses were hampered by large uncertainties in both of these numbers: the only available radial-velocity measurement was based on low-dispersion spectrograms taken from the Northern Hemisphere, and the distance modulus estimate was derived principally from old 25-brightest-stars data. Clearly a modern investigation of this cluster is long overdue. We have recently obtained new observations of both the cluster distance and velocity, and with these a firmer discussion of its orbit can now be made.

An image-tube spectrogram at ~ 125 Å mm^{-1} of NGC 5694 was taken with the Yale 1-m telescope at CTIO on 1975 September 1/2 during part of a larger program (Smith, Hesser, and Shawl 1976; Hesser and Shawl, in preparation). Measurement of the spectrum from Hα to Ca II K compared with five spectra of four radial-velocity standard stars on the same plate yielded $v_r = -174 \pm 28$ km s^{-1}. This value agrees within the errors of measurement with the earlier determination of $v_r = -187 \pm 27$ km s^{-1} (Mayall 1946, as discussed by Kinman 1959*a*), which Mayall obtained from the average of four spectra at 430 Å mm^{-1}. The result provides confidence that no serious errors exist in the radial-velocity part of the data, and we average the CTIO and Lick results to obtain $v_r = -180 \pm 19$ km s^{-1}.

The cluster distance modulus used in the older studies presents a more serious problem. The first available color-magnitude diagram for NGC 5694 (Harris 1975) reveals the giant branch beginning at $V \simeq 15^m.5$, $(B-V) \simeq 1^m.4$ and continuing downward to the limit of the study ($V_{lim} \approx 18^m$), but does not appear to resolve the horizontal branch. However, a preliminary analysis of some much deeper ($V_{lim} \sim 22^m$, $B_{lim} \sim 23^m$) photographic material recently obtained with the CTIO 4-m telescope (Harris, in preparation) shows an unmistakeable blue horizontal branch starting at $V_{HB} = 18^m.4 \pm 0.2$. With $M_V(\mathrm{HB}) = 0^m.6 \pm 0.3$ (Sandage 1970), $E_{B-V} = 0^m.08$ (Harris 1976), and $A_V/E_{B-V} = 3.3$ (Aannestad and Purcell 1973), we obtain $(m-M)_0 = 17^m.54 \pm 0.36$ and $D_\odot = 32 \pm 5$ kpc. This places the cluster significantly closer than the earlier estimate of $D_\odot = 42 \pm 12$ kpc (Kinman 1959*a*) and shows, not surprisingly for such a distant object, that the old brightest-stars estimate was in error. If the distance between the sun and galactic center is $R_0 = 9$ kpc (e.g. Harris 1976), then the galactocentric distance of NGC 5694 is $r = 26 \pm 5$ kpc.

To evaluate the orbit of the cluster, we use the "representative" galactic mass model of Innanen (1973), for which $R_0 = 9$ kpc and the rotational velocity at the sun is $\Theta \simeq 225$ km s^{-1}. Subtracting the component of Θ_0 along the cluster line of sight (with $v_r =$

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-180 km s^{-1} as quoted above) yields $v_{cl} = -273 \pm 19$ km s^{-1} as the motion of NGC 5694 with respect to a stationary point at the position of the sun. (The correction to v_r for the local standard of rest (LSR) turns out to be negligible, since the solar motion with respect to the LSR (Delhaye 1965) is nearly perpendicular to the cluster line of sight.) The value of v_{cl} is, of course, only a *lower* limit to the true velocity of NGC 5694 with respect to the galactic center itself since its transverse motion is unknown.

At $r = 26 \pm 5$ kpc the escape velocity for Innanen's (1973) standard mass model is $v_{esc} \approx 190 \pm 35$ km s^{-1} with respect to the galactic center.* The difference $|v_{cl}| - |v_{esc}| = 77$ km s^{-1} is larger than the combined errors in v_{cl} and v_{esc}, and implies that NGC 5694 must indeed be escaping from the Galaxy *unless* the conventional mass model is drastically wrong. In order to raise v_{esc} up to ~ 250 km s^{-1} we would have to set $\mathfrak{M}_{gal} \gtrsim 1.9 \times 10^{11}\, \mathfrak{M}_{\odot}$, i.e., almost double its presently estimated value. The reason for this is that adding mass *inside* $r = R_0$ would increase v_{esc}, but would also force a corresponding increase in Θ_0 (and hence v_{cl}; cf. the discussion of Harris (1975)) and so $|v_{cl}| - |v_{esc}|$ would decrease slightly (by 10 km s^{-1} for each 25 km s^{-1} increase in Θ_0). Thus the *assumption* that NGC 5694 is in a bound orbit appears to force the adoption of a "massive halo" for the Galaxy. Although uncertainties do still exist in the observed radial velocity and distance, we believe the current data now place sufficiently stringent limits to indicate that the more important problem is likely the galactic mass distribution itself.

If the conventional mass models are more or less correct, and NGC 5694 is in a hyperbolic orbit, then is it an intergalactic object which is simply "passing through," or is it a normal galactic globular cluster that has somehow been pushed into a higher-energy orbit? We feel that the latter hypothesis may be more likely, since other characteristics of NGC 5694 resemble those of the "normal" globular clusters instead of the extremely distant objects (Palomar clusters and/or dwarf spheroidal systems) which lie on the outer fringes of the galactic halo. These latter objects possess several distinctive characteristics (cf. Harris 1976 and references cited therein) that separate them from the more nearby clusters: (1) diffuse, low-density structures that would not survive close tidal encounters with the Galaxy; (2) extremely low heavy-element abundance; (3) peculiar color-magnitude diagrams with predominantly red horizontal branches and steep giant branches; (4) peculiar variable stars; and (5) nonisotropic distribution in space. NGC 5694, on the other hand, is a compact, moderately luminous cluster which does not differ in any obvious way *except* its space motion from many other typical halo clusters. It is hard to see how such a cluster could have formed in isolation in intergalactic space. While we plan to improve the precision with which the radial velocity and distance are known, we also suggest that calculations to trace back the orbit of NGC 5694 from its presently observed position and velocity (perhaps with various starting assumptions about its transverse motion) might prove valuable.

One additional parameter of the cluster orbit which we can estimate roughly is the *perigalactic* distance r_p, which is determined once the "tidal radius" of NGC 5694 is known. Although star counts of the type described by Peterson and King (1975) are preferable for determining tidal radii, such data are as yet unavailable for NGC 5694. Instead, concentric-aperture photometry can be used to estimate the tidal radius more crudely as $r_t \approx 12$ arc minutes (Harris, in preparation). With the integrated cluster magnitude of $V_t = 10.2$ (Peterson and King 1975) and a mass-to-light ratio $\mathfrak{M}/L \approx 1.5$ (Illingworth 1976), we obtain $\mathfrak{M}_{cl} \approx 1.1 \times 10^5 \mathfrak{M}_{\odot}$ for the total cluster mass. Finally, applying the equations of King (1962) and Peterson (1974) we find that the orbit of NGC 5694 reached perigalacticon at $r_p \approx 14$ kpc and has a minimum eccentricity $e_{min} = 0.32$ ($e = 1$ for a parabolic orbit). Thus NGC 5694 now appears to be twice as far away from the galactic center as its perigalactic point, which itself is well out in the halo.

The Magellanic Clouds appear to be the only obvious candidates with the right distance and sufficient mass to throw a halo globular cluster into a hyperbolic orbit, so it will be interesting to determine whether they could realistically have intersected the path of NGC 5694 during their last orbital passage. If the Clouds are indeed responsible for its present orbit, then it is also possible that NGC 5694 belonged originally to the cluster system of the Clouds and not the Galaxy. The forthcoming fainter color-magnitude study should provide further information on this possibility.

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*We use here a point-mass approximation for the Galaxy with $\mathfrak{M}_{gal} = 1.1 \times 10^{11}\mathfrak{M}_{\odot}$, following Innanen. Inspection of Innanen's detailed models shows that more than 95% of the mass lies within $r \sim 25$ kpc, and that the tabulated escape velocity in the disk at $r = 26$ kpc differs from our point-mass estimate by less than 5%.

REFERENCES

Aannestad, P. A., and Purcell, E. M. 1973, *Annual Rev. of Astr. and Astrophysics* **11**, 309.
Delhaye, J. 1965, in *Galactic Structure*, A. Blaauw and M. Schmidt, eds. (Chicago: University of Chicago Press), p. 61.
Harris, W E. 1975, *Ap. J. Suppl.* **29**, 397.
—— 1976 (submitted for publication).
Illingworth, G. 1976, *Ap. J.* **204**, 73.
Innanen, K. I. 1973, *Ap. and Space Sci.* **22**, 393.
King, I. R. 1962, *A.J.* **67**, 471.
Kinman, T. D. 1959*a*, *M.N.R.A.S.* **119**, 157.
—— 1959*b*, *ibid.* **119**, 559.
Mayall, N. U. 1946, *Ap. J.* **104**, 290.
Peterson, C. J. 1974, *Ap. J. (Letters)* **190**, L17.
Peterson, C. J., and King, I. R. 1975, *A.J.* **80**, 427.
Sandage, A. 1970, *Ap. J.* **162**, 841.
Sandage, A., and Wildey, R. 1967, *Ap. J.* **150**, 469.
Smith, M. G., Hesser, J. E., and Shawl, S. J. 1976, *Ap. J.* **206**, 66.
von Hoerner, S. 1955, *Zs. f. Ap.* **35**, 255.