THE NGC 5128 CLUSTER SYSTEM

Hugh C. Harris†

U. S. Naval Observatory

Gretchen L. H. Harris†

University of Waterloo

James E. Hesser†

Dominion Astrophysical Observatory
Hertzberg Institute of Physics

ABSTRACT: We review what has been learned about the globular clusters in NGC 5128 (Cen A). Two independent programs (our work at CTIO and Sharples' work at the AAT) have confirmed 87 objects as clusters in NGC 5128 from their velocities. We discuss the colors of the clusters, which are indicative of a wide range of metallicities, their velocities, and their origin as genuine globular clusters in this elliptical galaxy.

1. INTRODUCTION

The globular cluster systems in our Galaxy and M31 are well studied, and provide much of the data for the discussions at this conference. The information acquired about cluster systems in other spiral galaxies is more fragmentary because of their much larger distances and the greater observational difficulties for such systems. Because NGC 5128 is the closest large elliptical galaxy, it can, in some respects, play the same role for studying the clusters in elliptical galaxies that our Galaxy and M31 play for the clusters in spirals. We are fortunate that NGC 5128 is at a distance where three techniques for finding clusters all have some effectiveness: (1) the largest and brightest clusters have barely nonstellar images on plates or CCD frames taken in good seeing, (2) the galaxy's radial velocity ($\sim$550 km s^{-1}) allows velocities to be used to confirm membership of clusters in NGC 5128, and (3) star counts give statistical information about the total population of clusters and their distribution in the galaxy. No *single* technique is as effective as might be desired: at closer distances the third technique breaks down and the second only discriminates against background galaxies, while at larger distances the first technique is hopeless for ground-based observers and the second becomes very difficult. The combination, however, is effective.

†Visiting astronomer, Cerro Tololo Inter-American Observatory, National Optical Astronomy Observatories, operated by AURA, Inc., under contract with the National Science Foundation.

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This paper will concentrate on what has been learned about the NGC 5128 cluster system based primarily on two research programs. We have been pursuing cluster identification from Cerro Tololo Inter-American Observatory for six years using several approaches. Recently, Sharples has achieved excellent results using the multi-aperture fiber-fed spectrograph on the AAT to obtain spectra and velocities of more than 40 objects at a time. Half of the clusters have been confirmed during the 1986 observing season, so most of the present analysis is preliminary. Previous work has been reviewed at IAU Colloquium 68 (Hesser et al. 1981) and in the Astrophysical Journal (Hesser et al. 1984; G.Harris et al. 1984; H.Harris et al. 1984; Hesser et al. 1986).

2. IDENTIFICATION OF CLUSTERS

There are now 87 confirmed clusters in NGC 5128. Many were flagged as candidates by their nonstellar appearance on CTIO prime-focus plates during exhaustive visual searches of many plates by us, following the lead of Graham and Phillips (1980) and van den Bergh et al. (1981). Some, although missed in the visual searches, were flagged as nonstellar during an analysis of scans of the same plates with the COSMOS microdensitometer at Edinburgh (H.Harris et al. 1984). Radial velocities obtained at CTIO have confirmed membership in NGC 5128 for 47 clusters identified by their nonstellar character. Three more clusters were confirmed through velocities measured at CTIO of a random sample of objects projected near NGC 5128. Finally, 44 clusters (7 in common with the CTIO studies) were confirmed from their velocities by Sharples (1987) at the AAT as part of observations of a sample of 227 objects projected near NGC 5128. The nonstellar character of most of these clusters is *quite* subtle. However, a combination of careful visual inspection and COSMOS or PDS image analysis has proven very successful at finding clusters: six of the seven candidates published by Hesser et al. (1984) have now proven to be clusters, and fifteen of the twenty top candidates observed at CTIO this year were found to be clusters.

A histogram of the velocitites of all objects observed in NGC 5128 shows a large peak near 0 km s^{-1} (with a range from -192 to $+221$ km s^{-1}) and a broad distribution from 282 to 860 km s^{-1}. The bimodal nature of the distribution has allowed the decision about membership in NGC 5128 to be made without ambiguity for most objects. It is possible for foreground stars in our Galaxy's halo to have high velocities overlapping with the distribution of NGC 5128 velocities. However, such stars are sufficiently rare that probably none have been observed and misclassified. No background galaxies have been found in the random samples (although Sharples' sample excludes objects with very extended images). A few galaxies have been observed at CTIO among the cluster candidates with extended images, but their high velocities (of order 10,000 km s^{-1}) cause no confusion. Therefore, velocity discrimination is indeed very effective for assigning membership in NGC 5128. Another possible worry is that high luminosity stars in the spheroid of NGC 5128 have been observed and misclassified as clusters. This cannot be the case for the objects which were found by their extended images (47 objects out of 87). However, for objects found in the random samples, this sort of misclassification may be occurring occasionally. It is probably not happening often because the colors of clusters found in the random samples are all intermediate, while a magnitude-limited sample of supergiants might be expected to have a wider range of colors.

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3. THE CLUSTER LUMINOSITY FUNCTION

The numbers of *fainter* clusters have been estimated from star counts (both visual and automated) and are described by G.Harris et al. (1984). Combining star-count results with the individual confirmed clusters at the bright end gives the total cluster luminosity function shown in Figure 1. The figure includes all 77 confirmed clusters with projected distances from NGC 5128 of $1.6 \le R \le 16.1$ arcmin, in order to compare with the star counts in the same region. Also shown is a gaussian function with a peak $M_V = -7.1$ and $\sigma_V = 1.35$, similar to the luminosity functions found for cluster systems in the Galaxy and M31 by van den Bergh (1985). Assuming that the clusters in NGC 5128 obey the same function, then the best fit is obtained with a distance of 3.2 Mpc (with $E(B-V) = 0.1$) and a total of 900 clusters within the radial limits. (The total at *all* radii is then 1500, assuming that the clusters follow the halo light.) The distance could range from 2.5 Mpc to 4.0 Mpc and still remain marginally consistent with the data and these assumptions. The agreement between the data and the fitted curve is very satisfactory, the confirmed clusters being noticeably (but not surprisingly) incomplete for $V \ge 18$. Whether the clusters in NGC 5128 do, in fact, obey the adopted gaussian function can best be decided after measuring the distance to NGC 5128 independently, although this measurement is difficult to make with the required accuracy of $\le$20%. A distance near 3 Mpc has recently been suggested by the relatively low velocity dispersion measured for the bulge light (Wilkinson et al. 1986), and a small distance is implied by the magnitude of Supernova 1986G currently being analyzed by several groups.

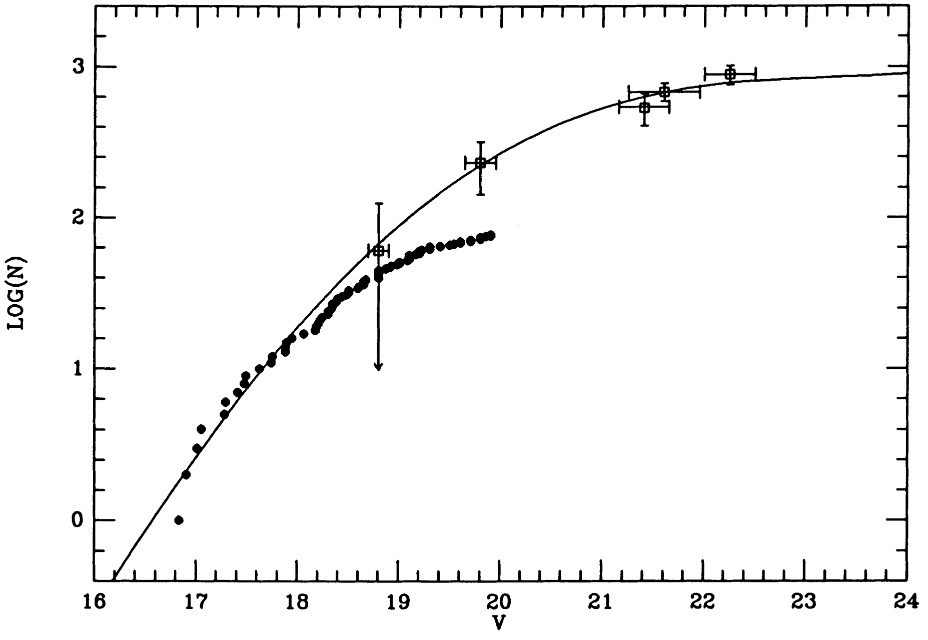

Fig. 1. Cumulative luminosity function of clusters with $1.6 \le R \le 16.1$ arcmin. Confirmed clusters are shown by filled circles. Results from image counts are shown by open squares. The line is a gaussian fit to the data (see text).

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Alternatively, if the distance is as large as 5 Mpc (a value often used in the literature), then the clusters must have a luminosity function with some combination of a brighter peak, a larger dispersion in the luminosity function, and/or a non-gaussian distribution.

Are many bright, compact clusters being missed in our searches, particularly in view of the tendency for the inner clusters to be more compact (Hesser et al. 1984), or are the star counts in error, giving a misleading luminosity function in Figure 1? Four arguments suggest not. (Some of this evidence is discussed more fully by H.Harris et al. 1984.) (1) The repeated recovery of extended objects during several independent searches is good enough that we think we have found most of the bright, extended objects. (2) Most of the candidates that we have classified as only very marginally extended have turned out to have low velocities indicative of their being foreground stars. (3) The size distribution of objects with $V \leq 18$ measured in the COSMOS analysis did not show the clump of very marginally extended objects near the search limit that we would expect to see if many compact clusters were being missed. (4) Few clusters have been found from velocities of random objects near NGC 5128. (The selection of objects observed at CTIO has excluded extremely blue and red objects, so is actually not totally random. See Hesser et al. 1984.) Only 3 clusters were found among 32 random objects observed at CTIO having $16.0 \leq V \leq 18.5$ and projected in two fields just northeast and southwest of the dust lane, and one resolved cluster lies in these fields. In Figure 2, the left panel shows the color-magnitude diagram of these fields. At a radius of 5 arcmin from NGC 5128, the star counts show 2.3 objects arcmin^{-2} with $16.0 \leq V \leq 18.5$, and for the distance and cluster population found in the preceding paragraph, we expect 2.7 clusters arcmin^{-2} at this radius, of which 4.5% should be within the magnitude range. Therefore, we expect 4 clusters within this magnitude range in the two fields with random objects observed at CTIO, and 4 clusters are found. The star counts have now been strengthened by Sharples' data.

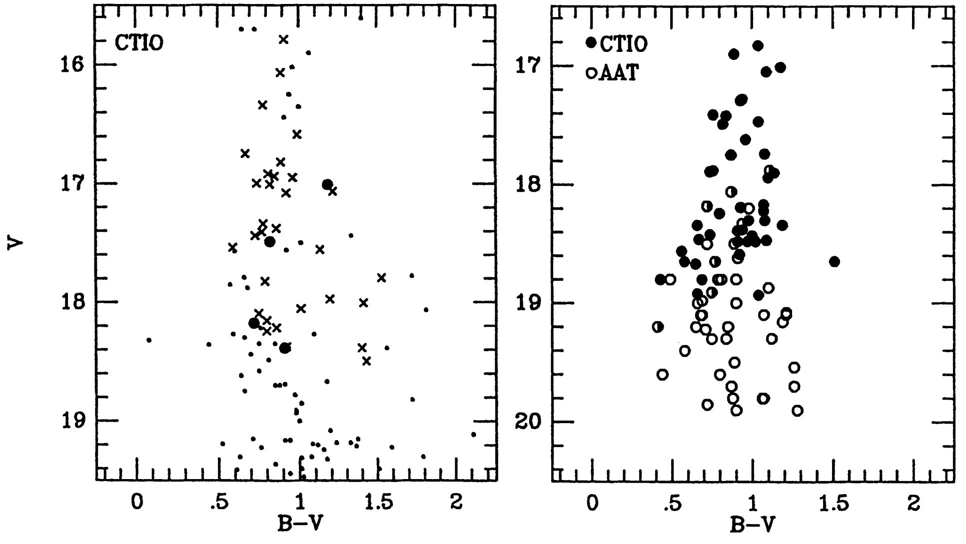

Fig. 2. Left panel: objects in two fields observed at CTIO (filled circles are clusters, crosses are stars). Right panel: all confirmed clusters.

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Only 29 clusters were found among 194 objects with $18.0 \leq V \leq 19.5$ observed at the AAT, and only one cluster brighter than 18.5 was found that had not already been identified and confirmed at CTIO from its nonstellar appearance. The star counts show 2.7 objects arcmin^{-2} with $18.0 \leq V \leq 19.5$, and we expect 15% of all clusters to have these magnitudes. Therefore, we expect 33 of the 194 AAT objects to be clusters. The consistency between the numbers of clusters expected and found adds confidence that the observed luminosity function in Figure 1 is not too far in error. Therefore, the luminosity distribution of the 87 confirmed clusters provides not only a lower limit, but also probably a very good approximation, to the true luminosity function at the bright end (brighter than V ~ 18).

4. CLUSTER COLORS

The right panel of Figure 2 shows the color-magnitude diagram of all confirmed clusters in NGC 5128. They have measured B−V colors between 0.41 and 1.28. The one exception is Cluster 42, lying 6 arcminutes west of the center of NGC 5128, with B−V = 1.51. It may lie behind part of the dust lane. A few other confirmed clusters may also be reddened by dust in NGC 5128, but most of the clusters lie well away from most detectable dust (Pennington 1984), so the distribution of cluster colors is probably not affected much by internal reddening. All clusters have a foreground reddening of E(B−V) ≈ 0.10 (van den Bergh 1976), and this amount has been subtracted from the observed colors in the following discussion. The NGC 5128 clusters appear to cover a larger range of colors than do the globular clusters in our Galaxy. The two distributions are shown in Figure 3, where the observed colors for Galactic globulars have been taken from Peterson (1986) and reddenings have been taken from Webbink (1985). The same result is found using colors for Galactic globulars from Reed (1985).

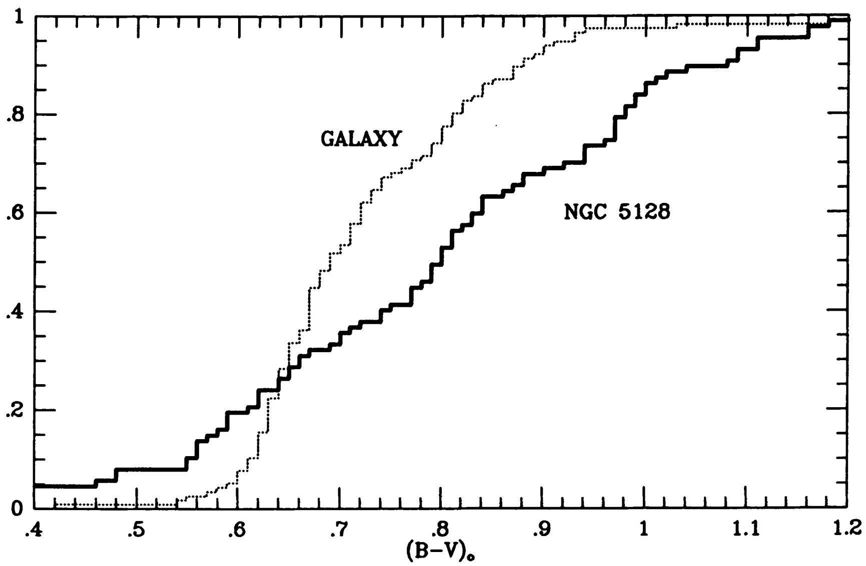

Fig. 3. Cumulative distribution of colors, corrected for reddening, for clusters in NGC 5128 compared with our Galaxy.

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The blue end of the color distribution in NGC 5128 is similar to that in our Galaxy with the exception of four clusters in NGC 5128 with $0.40 \leq B-V \leq 0.50$. Cluster 46 = G331 has been identified as a relatively blue cluster independently by Sharples and by us, and it appears nonstellar, so it, at least, is a real blue cluster. They *may* be younger than true globulars. They all lie at projected radii $\leq$10 arcmin, so they could have an origin associated with the dust lane. However, none lie very close to the dust lane – they are not the blue objects noted by van den Bergh (1976) along the dust lane – nor are they the blue knots identified along the optical jet by Blanco et al. (1975), although some do lie in the region of the optical jet. They are not as blue as many clusters in the LMC and M33 (van den Bergh 1981; Christian 1987). Clusters in the LMC with similar B−V colors have ages of 3×10^8 to 3×10^9 years (Hodge 1983; Mateo 1987). However, a comparison with LMC clusters should take into account possible metallicity differences; the present abundances of HII regions in NGC 5128 are metal-rich but uncertain (Dufour et al. 1979; Phillips 1981), suggesting ages younger than LMC clusters with the same $(B-V)_o$. Therefore, intermediate ages near 3×10^8 years are plausible for these relatively blue clusters.

The clusters in NGC 5128 extend considerably redder than those in the Galaxy: more than 30% of the clusters are redder than $(B-V)_o = 0.90$, while in the Galaxy only 10% are so red. There are two reasons for believing that these clusters (with possibly a couple of exceptions) do not have unusually high reddening: their infrared colors (Frogel 1984) indicate a cool, metal-rich population, rather than a highly reddened population, and several of these red clusters lie well out in the halo where it is unlikely that they are affected by internal dust. We are attempting to measure the line strengths of our CTIO spectra to investigate this question further. Many of the blue SIT spectra are noisy enough that they do not give meaningful results, and the red CCD spectra of the Ca triplet lines, while having better signal-to-noise, do not show enough sensitivity in the Ca lines to be useful. However, the better spectra show a correlation between the line strengths and B−V colors, with the redder clusters at least as strong-lined as metal-rich Galactic globulars.

Comparing the color distribution with other galaxies would be desirable. Two possibilities are M31 and M87, but comparisons do not appear to be meaningful at present. The colors of Class A and B clusters in the southeast half of M31 (where reddening within M31 is a minimum) taken from Battistini et al. (1986) show a distribution even more extended than in NGC 5128. It is likely that some younger disk clusters, reddened clusters, and background galaxies are being included in the M31 sample. Similarly, the B−R colors of clusters in M87 in Zones 1, 2, and 3 from Strom et al. (1981), transformed to B−V, also show a distribution more extended than in NGC 5128. Spectroscopy by Mould et al. (1986) shows that the bluest and reddest objects are generally not clusters, but more data are needed to define the true color distribution of M87 clusters.

The JHK colors measured and discussed by Frogel (1984) provide strong evidence that the red clusters are indeed quite metal rich. The red (B−V) and (V−K) colors imply high metal abundance, while the lack of very red (J−K) colors indicates a lack of carbon stars in the clusters and hence an old age ($\geq 10^{10}$ yr). It appears that the distribution of metallicities of clusters in NGC 5128 is similar at the metal-poor end to clusters in the Galaxy, but includes a higher fraction of metal-rich clusters extending to higher metallicities than in the Galaxy.

Earlier work gave the tentative suggestion that a gradient in the cluster colors might exist (Hesser et al. 1984), implying a metallicity gradient in the cluster system. Figure 4 shows that no gradient is visible with the more complete

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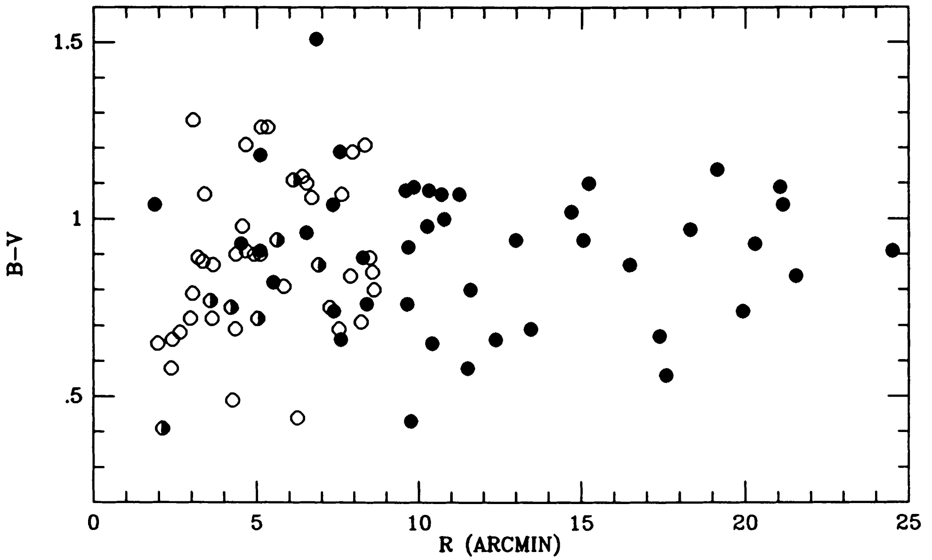

Fig. 4. Colors of confirmed clusters vs. projected distance from the center of NGC 5128. Filled circles are clusters observed at CTIO, and open circles at AAT.

data now available. Possibly a few points in Figure 4 are biasing this conclusion because of either the presence of younger, bluer clusters at small radii or the higher likelihood of internal reddening at small radii. However, with the identification of clusters with $(B-V)_o \sim 1.0$ at projected radii of 15 to 20 arcmin, it appears unlikely that any gradient other than a very weak one can exist in the halo of NGC 5128.

5. CLUSTER VELOCITIES

Globular cluster velocities provide an excellent probe of the dynamics of the halo of galaxies. Hesser et al. (1986) suggested that the outer clusters in NGC 5128 (projected more than about 12 arcminutes from the center) reflected the potential of the unperturbed elliptical galaxy, but that the inner clusters showed effects from the interaction or merger which is thought to have produced the dust lane. In the year since that paper was prepared, independent data have become available from our CCD red spectra taken at CTIO and from Sharples' spectra taken at the AAT. These data sets provide necessary checks against errors in velocities (systematic, or random due to low signal-to-noise) from the earlier SIT spectra, as well as more than doubling the number of clusters with measured velocities.

The present data are shown in Figure 5. They have not yet been analyzed for significant trends, but some preliminary results can be indicated. The surprisingly large mean velocity of the inner clusters reported by Hesser et al. (1986) is not supported by the much larger sample of (primarily fainter) inner clusters. However, the possible rotation of the cluster system, both about the minor axis (NE approaching) and about the major axis (SE approaching) is still marginally evident. The mean velocity of the clusters on the southeast side of the major axis is smaller than the mean on the northwest side by 60 km s^{-1}. This difference

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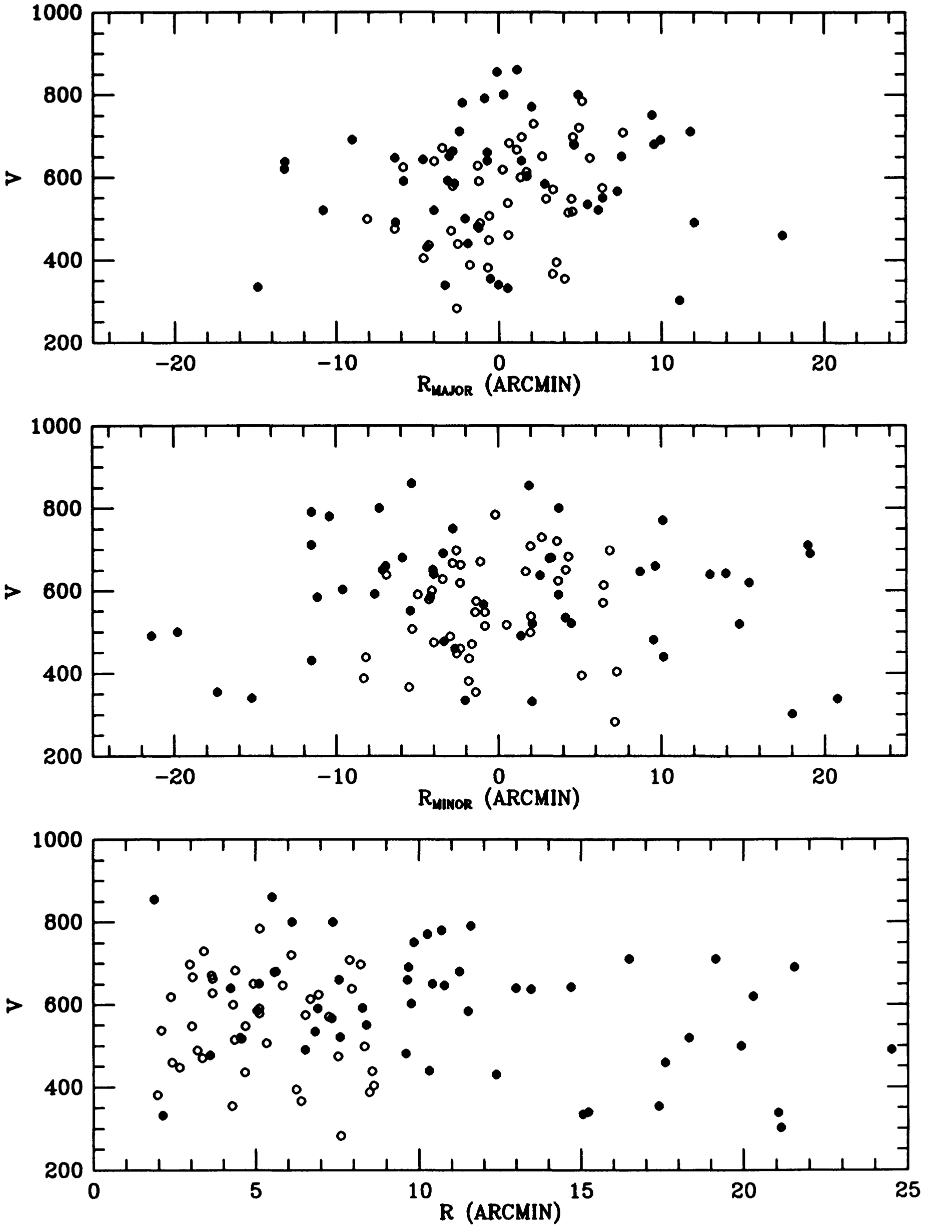

Fig. 5. Radial velocities of all confirmed clusters from the CTIO sample (filled circles) and from the AAT sample (open circles). The top panel shows velocities vs. projected distance from the major axis of NGC 5128 (with SE toward the left and NW toward the right), the middle panel is vs. distance from the minor axis (NE to the left, SW to the right), and the bottom panel is vs. radial distance.

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is probably significant, but is certainly much less than the amplitude of the disk rotation curve (approximately 600 km s^{-1}). A solution for systematic rotation is needed to access its reality, and will be done.

The velocity dispersion of the clusters is nearly independent of radius (Figure 5): for radii less than 5 arcmin and radii greater than 10 arcmin, the observed dispersions are 130 ± 20 and 154 ± 20 km s^{-1}, respectively. Using the projected mass estimator (Heisler et al. 1985) with $f_{PM}=48/\pi$, the mass is $7\text{x}10^{11}$ $M_\odot$for a distance of 3.2 Mpc (scaling as D/3.2), the magnitude is V=5.9 (van den Bergh 1976), and the mass/light ratio is 17 $M_\odot/L_\odot$(scaling as 3.2/D) within a radius of ~20 kpc.

6. ORIGIN OF THE CLUSTERS

In comparing the clusters in NGC 5128 with globular clusters in other galaxies, or in using the clusters to estimate the distance or mass of NGC 5128, for example, we are implicitly assuming that the clusters are, in fact, genuine globular clusters representative of a normal, large elliptical galaxy. Arguments for this assumption are of two types: first, consistency arguments that the properties (colors, magnitudes, spectral types, sizes, spatial distribution, etc.) of the clusters are generally what are expected for a normal globular cluster system; and second, difficulties in understanding the origin of the cluster system in ways other than formation early in the history of a large elliptical. Arguments of the first type have been presented as part of several papers (Hesser et al. 1984; H.Harris 1984; this paper).

Within the framework of the interaction picture for NGC 5128, with a relatively low mass, gas-rich galaxy falling into NGC 5128 some $3\text{x}10^8$ years ago (Tubbs 1980), not more than a small fraction of the clusters we observe can have come from the intruding galaxy, because of the low halo mass expected for such an intruder and the lack of disk-like rotation seen either in the bulge light of NGC 5128 or in the cluster system. Nor can more than a small fraction have been formed during the interaction, because of their red colors and their spatial distribution away from the dust lane. The strongest arguments that some of the clusters are *not* normal globulars may be that more clusters tend to be found in the northeast and southwest quadrants of the inner bulge (Sharples 1987), that the cluster system may share some small amount of disk-like rotation, and that some clusters are bluer than Galactic globulars with ages consistent with age estimates for the dust lane. However, even these arguments would suggest that not more than a small fraction of the confirmed clusters are other than normal globulars. The multiple shells seen at large radii in NGC 5128 suggest that one or more interactions may have occurred longer ago than $3\text{x}10^8$ years (Malin et al. 1983), events presumably unrelated to the present dust lane. It is more difficult to argue for or against a connection between such early interactions and the properties of the clusters. However, the overall evidence indicates to us that the large majority of clusters presently being studied probably do, indeed, represent globular clusters in a normal elliptical galaxy.

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DISCUSSION

GRAHAM: Did the new CCD velocities based on the λ 8500 Ca II lines agree with the earlier SIT velocities?

HARRIS, H: For most objects the agreement was good (within the estimated errors). For a couple of objects the CCD velocities differed by more than expected, apparently due to a tail on the error distribution of SIT velocities.

HESSER: A high percentage of the most discrepant velocities appear to be due to velocities from single, relatively short exposures from the SIT vidicon. Velocities from multiple SIT exposures appear to agree much better with our CCD or Sharples' IPCS velocities.

RACINE: How many candidates were identified on the basis of their non stellar appearance and for what fraction of those do you have spectroscopic confirmations?

HARRIS, H: Approximately 75% of the non stellar cluster candidates that we have observed spectroscopically have proven to be clusters. Forty-seven clusters have been confirmed this way.

GNEDIN: Your last slide shows "Cluster mag. being formed by the jet". What do you mean by this? Is there a real connection between clusters and jets?

HARRIS, H.: I included this possibility as a (quite speculative) mechanism to explain Sharples' finding more clusters in the NE and SW quadrants of the inner halo.

GRAHAM: Some blue clusters are being formed out in the NE radio lobe. One is on the S end of knot A (cf Blanco et al. 1975). Another is knot D identified in that paper. Both are slightly non stellar, blue continuum objects without strong emission lines in their spectrum.

HUCHRA: Why did you pick such a large value of the projection factor ($48/\pi$) in the projected mass formula of Bahcall and Tremaine? In the outskirts of the galaxy, the cluster orbits are more likely to be circular. Bahcall and Tremaine in that, suggest using a factor of $24/\pi$.

HARRIS, H.: A small factor may be appropriate. We have no information on the orbits of the clusters in NGC 5128.

HANES: Some decades ago Shklovsky commented that he saw more globular clusters in the quadrant of the jet in M 87 than in the other three quadrants. Later (deeper) analysis seems to have ruled that out, but it is provocative that you seem to be finding similar effects here.

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DI FAZIO: Did you notice any correlation between the shape of the projected distribution of Cen A clusters and the axis of the jet or of the radio lobes? If yes, can this be due to the relatively small number of objects that you considered?

HARRIS, H.: Our CTIO sample of clusters has a slightly elliptical distribution oriented with the outer isophotes of NGC 5128. The combined CTIO and AAT samples may be elliptical, but we have not yet estimated the statistical significance.

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