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DYNAMICAL EVIDENCE FOR A MASSIVE, YOUNG GLOBULAR CLUSTER IN NGC 1569[1]

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ABSTRACT

Recent high-resolution observations with the *Hubble Space Telescope* (*HST*) reveal that star clusters of extraordinary luminosity and compactness are commonly found in a variety of starburst systems. There has been much speculation that these clusters represent present-day analogs of young globular clusters. Using the HIRES echelle spectrograph on the Keck 10 m telescope, we obtained high-dispersion optical spectra of one of the "super star clusters" (cluster "A") in the nearby dwarf galaxy NGC 1569. The size of the cluster is known from published *HST* images. The line-of-sight velocity dispersion ($\sigma_* = 15.7 \pm 1.5$ km s^{-1}) has been measured from a cross-correlation analysis of its integrated spectrum at visual wavelengths. If the cluster is gravitationally bound and the velocities are isotropic, application of the virial theorem implies that the cluster has a total stellar mass of $(3.3 \pm 0.5) \times 10^5\ M_\odot$. This object's mass, mass density, and probable mass-to-light ratio after aging 10–15 Gyr are fully consistent with the typical values of Galactic globular clusters. Our result strongly suggests that at least some of the luminous, compact, young star clusters being discovered with *HST* will indeed evolve into normal globular clusters of the type seen in the Milky Way.

Subject headings: galaxies: individual (NGC 1569) — galaxies: irregular — galaxies: starburst — galaxies: star clusters — globular clusters: general

1. INTRODUCTION

In the last few years, *Hubble Space Telescope* (*HST*) imaging studies of a variety of extragalactic star-forming systems have identified a widespread new class of star clusters. The compactness and high luminosities of these objects, coupled with their inferred youth, have stimulated speculation that they represent present-day analogs of young globular clusters. Although the existence of a few such "super star clusters" had been known from previous ground-based studies (e.g., Arp & Sandage 1985; Melnick, Moles, & Terlevich 1985; Lutz 1991), it took the resolving power of *HST* to demonstrate the prevalence of this phenomenon. Such clusters appear to be a common feature in amorphous galaxies (O'Connell, Gallagher, & Hunter 1994; Hunter, O'Connell, & Gallagher 1994; O'Connell et al. 1995), merging and interacting systems (Holtzman et al. 1992; Whitmore et al. 1993; Whitmore & Schweizer 1995), circumnuclear star-forming rings (Benedict et al. 1993; Barth et al. 1995; Bower & Wilson 1995; Maoz et al. 1996), and various other starburst systems (Conti & Vacca 1994; Vacca 1994; Meurer et al. 1995).

That globular clusters may be forming in the present epoch is an exciting development, as observational studies of such a process are relevant to issues ranging from large-scale star formation to galaxy formation and evolution. The hypothesis that the recently discovered clusters are young *globular* clusters rests on three pieces of evidence. First, these clusters are generally quite compact, being unresolved or marginally resolved in *HST* images of relatively nearby galaxies, which implies that they have half-light radii of only a few parsecs, similar to the sizes of Galactic globular clusters. Second, the brightest members have rather extraordinary luminosities, in many cases surpassing that of the R136 cluster in the center of the 30 Doradus complex in the Large Magellanic Cloud. Some of the clusters in the studies mentioned above, for instance, have absolute visual magnitudes exceeding −14 to −15; for comparison, $M_V = -11.3$ mag for R136 (O'Connell et al. 1994). Finally, the blue optical continuum colors, and, where available, the amount of ultraviolet radiation, indicate ages ranging from a few to 500 Myr. The presence of young stars has been confirmed unambiguously in several cases where spectroscopy with ground-based facilities (Arp & Sandage 1985; Melnick et al. 1985; Schweizer & Seitzer 1993; Prada, Greve, & McKeith 1994; Zepf et al. 1995) or *HST* (Leitherer et al. 1996; Conti, Leitherer, & Vacca 1996) has been feasible. Population synthesis models generally indicate that the luminosities of these clusters will fade to the observed luminosities of old globular clusters in 10–15 Gyr, provided that they are bound and dynamical evolution does not dissolve them. The shortness of the expected timescale for expansion, as deduced from the small physical dimensions, relative to their ages can be taken as evidence that most of the clusters may in fact be gravitationally bound (Whitmore et al. 1993; Whitmore & Schweizer 1995; Maoz et al. 1996). The masses derived from the models lie in the range found in Galactic globular clusters.

The arguments in favor of the globular cluster interpretation would be considerably strengthened by a *direct*, model-independent measurement of the cluster masses. Moreover, by combining the mass and the present luminosity with a model prediction of the luminosity evolution, one can compare the future mass-to-light ratio of the cluster to that of evolved globular clusters. Such a comparison can put meaningful constraints on the stellar population, and hence the initial mass function, of the young clusters.

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[1] Based on observations obtained at the W. M. Keck Observatory.

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This Letter reports the first attempt to measure the dynamical mass of one of these star clusters. The observations consist of high-dispersion (echelle) spectra of one of the two luminous star clusters in the central region of the nearby dwarf galaxy NGC 1569, which has recently been studied by O'Connell et al. (1994) using *HST*. For an overview of the general properties of the galaxy and its two bright clusters, consult Arp & Sandage (1985), Israel (1988), and O'Connell et al. (1994). The line-of-sight stellar velocity dispersion is combined with the previously reported size measurement to estimate the dynamical mass. The derived cluster mass ($\sim 3.3 \times 10^5\ M_\odot$) falls slightly higher than the peak of the mass function of evolved globular clusters in the Milky Way. Here, we restrict our attention mainly to the measurement of the velocity dispersion of the cluster in NGC 1569 and discussion of its implications. Ho & Filippenko (1996) present data for additional similar star clusters, and a future paper will analyze other information on the stellar population, gas kinematics, and interstellar absorption.

2. OBSERVATIONS AND ANALYSIS

On 1996 January 9 UT, we took high-dispersion spectra of the brighter of the two prominent clusters in NGC 1569 (cluster "A," hereafter NGC 1569-A; $V = 14.8$ mag; O'Connell et al. 1994) using the HIRES echelle spectrograph (Vogt et al. 1994) with the Keck 10 m telescope on Mauna Kea, Hawaii. Four consecutive half-hour exposures were obtained through a $1\farcs15 \times 7''$ slit. The full spectral range recorded wavelengths from ~3900 to 6280 Å in 34 spectral orders. The final spectral resolution, as determined from the profiles of the comparison lamp lines, is $R \approx 38{,}000$ (full width at half-maximum = 7.9 km s^{-1}). We also took brief exposures of several bright stars of known spectral types for application of the cross-correlation method to derive velocity dispersions. The program object and standard stars were interleaved with exposures of thorium and argon hollow cathode comparison lamps to monitor shifts in the wavelength scale. The initial data reduction closely followed standard procedures for echelle spectroscopy (e.g., Ho & Filippenko 1995), with a few minor modifications described in Ho & Filippenko (1996), where additional details concerning the observing strategy and instrument setup are also given. The one-dimensional spectra were extracted with a constant effective aperture of $1\farcs15 \times 2\farcs05$. The background signal was determined by averaging two adjacent regions on either side of the object. Within the extraction aperture, the light from the underlying galaxy is about 5 times fainter than that from the cluster; moreover, the stellar features of the background are very weak, and inaccuracies in background subtraction should have a minor effect on our analysis.

Our principal aim is to derive the line-of-sight velocity dispersion of the stellar component of NGC 1569-A. A number of studies based on different lines of evidence have concluded that the cluster is in its "postburst" phase, with an age of ~10–20 Myr (Israel 1988; Israel & de Bruyn 1988; Waller 1991; O'Connell et al. 1994). The relative youth of the cluster poses a set of complications not normally encountered in the measurement of velocity dispersions of old stellar populations. Based on a blue (~3200–4500 Å) spectrum of NGC 1569-A, Arp & Sandage (1985) determined an average spectral type of A0 Iab for the cluster. While weak metal lines can be easily discerned in our high-dispersion spectra at these wavelengths, they cannot be used for velocity dispersion measurement in our case because the line widths expected are dominated by other sources of line broadening intrinsic to stars of this spectral type. In early-A supergiants, both macroturbulent and microturbulent motions in the unstable atmospheres, as well as mild rotational broadening, broaden the lines by an amount comparable to the velocities anticipated from the virial motions of the individual stars. Hence, one must use portions of the spectrum whose flux is not dominated by early-type supergiants.

We base our analysis on the region of the spectrum from ~5000 to 6280 Å, which we argue below is suitable for measuring velocity dispersions. According to stellar population models (e.g., Bruzual & Charlot 1993), the spectrum of a cluster with an age of ~10 Myr comes largely from supergiants at wavelengths near and redward of the V band. In particular, a substantial fraction of the light should come from cool (F-M) supergiants (O'Connell 1996), as supported by the detection of strong Ca II infrared triplet absorption lines (Prada et al. 1994). Although the contribution from early (A and B) supergiants at these wavelengths is still not negligible, their spectra are relatively featureless compared to those of cool supergiants (e.g., Jacoby, Hunter, & Christian 1984). We neglected to take spectra of early-type supergiants during our observing run, but J. K. McCarthy kindly provided us with a spectrum of the star 177-A, a low-metallicity A0 supergiant in M33 observed with HIRES in a configuration nearly identical to the one used here (McCarthy et al. 1995). The comparison with the M33 star may be appropriate given the low oxygen abundance of NGC 1569 (Hunter, Gallagher, & Rautenkranz 1982). We confirmed that very few metal lines are found in the A0 Ia star at these wavelengths, and virtually none of the lines seen in the spectrum of NGC 1569-A are visible. By contrast, nearly all of the features seen in the cluster spectrum can be identified with metal lines in the G to M giants and supergiants we observed. Similarly, the flux of a 10 Myr old cluster at these wavelengths also comes partly from early-B stars still on the main sequence (O'Connell 1996), but such stars were verified to be nearly featureless in the region of interest.

To what extent can velocity dispersions be measured from an integrated spectrum dominated by the light of cool supergiants? In studies of old stellar populations (e.g., Illingworth 1976; Tonry & Davis 1979), the velocity template stars used are red *giants*, whose lines are intrinsically narrow and generally unresolved. Due principally to the effects of macroturbulence, the line widths of cool supergiants, on the other hand, are *not* negligible, typically having $\sigma \approx 9$ km s^{-1} for types F5–K5, with a spread about the mean of perhaps 1.5 km s^{-1} (Gray & Toner 1987). However, as long as the mass of the cluster is not too small, we should be able to extract its velocity dispersion using a cool supergiant as template.

The pattern of absorption lines in NGC 1569-A grossly resembles that of the template HR 2289 (46 ψ' Aur; see Ho & Filippenko 1996), listed as K5-M0 Iab-Ib in the Bright Star Catalog, although in detail it seems to match that of HR 3422 (G8 IV) more closely, suggesting that the cluster supergiants may have somewhat higher effective temperatures than K5-M0. Unfortunately, HR 2289 was the only supergiant we observed. To obtain a preliminary result, we adopt the following strategy. We use HR 3422 as the template to obtain an initial value of the velocity dispersion, and then we subtract from it in quadrature an amount expected to be due to the intrinsic widths of the supergiants. Note that using a subgiant

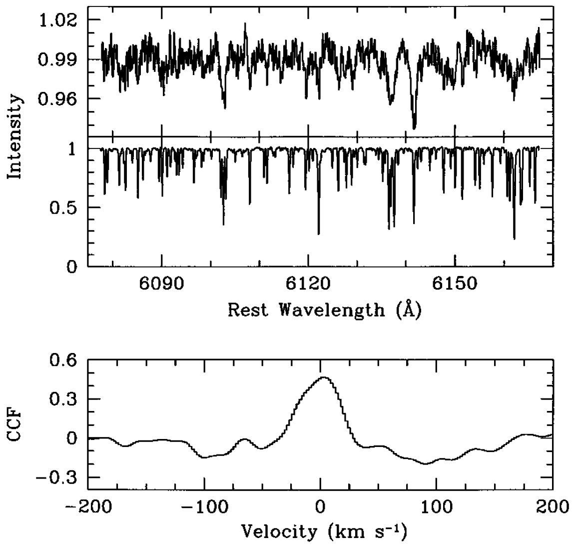

FIG. 1.—Example of the cross-correlation technique applied to one of the spectral orders. *Top panel* shows the spectrum of NGC 1569-A and the *middle panel* the template star HR 3422 (G8 IV), both normalized to unity and shifted to their rest frame. The cluster spectrum has been smoothed with a boxcar function of 3 pixels (6.4 km s^{-1}) in order to slightly improve the S/N for the sake of the presentation. *Bottom panel* plots the cross-correlation function (CCF) between the cluster and the star. The width of the main peak of the CCF is related to the velocity dispersion of the object, and the relation between the quantities is determined by empirical tests. In this order, the S/N per pixel of the continuum in the cluster (before smoothing) ranges from 80 at the blue end to 120 at the red end. The corresponding values for the star are S/N = 320–490.

as the template should not affect the derived dispersion, since rotational broadening in cool subgiants remains insignificant (Smith & Dominy 1979) and their macroturbulent motions are even smaller than in late-type giants (Gray & Toner 1986).

We applied the cross-correlation method of Tonry & Davis (1979) to the spectral orders between 5000 and 6280 Å, using the G8 IV star as the template. After excluding several orders having low signal-to-noise ratios (S/N) and/or lines of very low contrast, the final six usable orders yielded an average velocity dispersion of 18.1 km s^{-1}, with a standard deviation of 1.1 km s^{-1}. An example of one of the orders is shown in Figure 1. Assuming that cool supergiants have intrinsic line widths of 9 km s^{-1} (Gray & Toner 1987), we estimate that the line-of-sight component of the velocity dispersion arising from gravitational motions is $\sigma_* = 15.7 \pm 1.5$ km s^{-1}, where the error is simply a conservative guess of the uncertainty in our procedure. This value lies near the top end of the distribution of velocity dispersions for Galactic globular clusters (Illingworth 1976; Mandushev, Spassova, & Staneva 1991).

3. THE DYNAMICAL MASS OF THE CLUSTER

If NGC 1569-A is gravitationally bound, the virial theorem can be used to obtain the total mass of the cluster, provided that an effective gravitational radius can be measured for the system: $M = 3\sigma_*^2 R/G$. This simple relation assumes that (1) all the stars have equal masses, (2) the cluster is spherically symmetric, and (3) the velocity distribution is isotropic [$\sigma^2(\text{total}) = 3\sigma_*^2$]. Unlike the case of star clusters in the Galaxy and in some members of the Local Group, a detailed radial profile is not yet available for NGC 1569-A, and hence we cannot apply the somewhat more sophisticated formalism described, for instance, by Illingworth (1976). Adopting a half-light radius of 1.9 ± 0.2 pc (from Meurer et al. 1995, after adjusting to the distance of 2.5 Mpc preferred by O'Connell et al. 1994) as a reasonable approximation of the effective radius, we obtain $M = (3.3 \pm 0.5) \times 10^5\ M_\odot$.

How reliable is this mass estimate? Let us briefly examine the likely consequences of our main assumptions. The use of the virial theorem to derive the mass requires the cluster to be bound and dynamically relaxed. The first condition seems very likely to be satisfied; given the compactness of the cluster, any plausible expansion timescale is shorter than 1 Myr, whereas the estimated age of the cluster is at least an order of magnitude larger. However, if NGC 1569-A is indeed as massive as a typical globular cluster, it is unlikely to have completely virialized, since the relaxation time of most globular clusters is on the order of 10^9 yr (Binney & Tremaine 1987). Our measured velocity dispersion therefore underestimates the value it will attain when the cluster is truly virialized, and the derived mass represents a lower limit. The assumption that all the stars have equal masses obviously is a gross oversimplification. However, relaxing it will also increase our mass estimate. From a comparison of globular clusters whose dynamical masses have been determined using both single-mass and multi-mass models, Mandushev et al. (1991) conclude that the former tends to underestimate the masses by about a factor of 2. Finally, from a comparison of velocity dispersions obtained from spatially integrated spectra versus those computed from radial velocities of individual stars, Zaggia, Capaccioli, & Piotto (1993) find that the former method systematically biases the dispersions to lower values.

Of all the conventional parameterizations of the cluster size, the half-light radius appears to be the most robust characterization, since it is the least sensitive to evolutionary or environmental effects (van den Bergh, Morbey, & Pazder 1991). The angular size of NGC 1569-A, however, is not known to high accuracy (the images were taken prior to the *HST* refurbishment mission), and lack of a reliable distance determination to the galaxy further blurs its true linear size. Our adopted distance of 2.5 Mpc stems from a rather provisional evaluation of the resolved supergiant population surrounding the cluster (O'Connell et al. 1994). A survey of other published distances for the galaxy (e.g., Israel 1988; Tully 1988; Hunter et al. 1989) gives a range of 1.6–4.7 Mpc. Nevertheless, since the size of the cluster only enters linearly into the virial equation, its uncertainty has a less severe effect on the mass estimate than that associated with the velocity dispersion.

Previous mass estimates of NGC 1569-A and other objects of its kind (see § 1) have been highly uncertain, since they invariably relied on stellar population models that depend on a large number of poorly constrained parameters. The total stellar mass, in particular, is very difficult to obtain, since virtually all of the observables in such clusters trace the young, massive stars, which comprise only a fraction of the total mass for a normal initial mass function. The present study aims to bypass these complications by obtaining a direct measurement of the dynamical mass. Although the exact mass of NGC 1569-A is still difficult to pin down at the moment, there seems to be little doubt that it is indeed quite large, most likely on the order of (2–6) × $10^5\ M_\odot$. This value falls comfortably within the range of masses of Galactic globular clusters, whose average and median values are, respectively, 1.9×10^5 and $8.1 \times 10^4\ M_\odot$ (Mandushev et al. 1991). Most of the assumptions inherent in our calculation, in fact, bias the mass toward lower values; hence, the true mass may be even higher than our nominal estimate of $3.3 \times 10^5\ M_\odot$. NGC 1569-A is extremely compact: its half-light radius is merely 1.9 pc, comparable to, and perhaps a bit smaller than, that of the average globular cluster (Mandushev et al. 1991; van den Bergh et al. 1991). It follows, therefore, that its mass density ($1.1 \times 10^4\ M_\odot$ pc^{-3}) is at least as large as that of typical Galactic globular clusters. Since dynamical evolution will cause the cluster to expand as it ages (Elson 1992), the density of NGC 1569-A may not be very unusual.

Finally, it is worth considering the mass-to-light ratio of the cluster. With standard parameters, evolutionary synthesis calculations (e.g., Bruzual & Charlot 1993) predict that the visual light of a 10 Myr cluster will fade by about 6–7 mag in 10–15 Gyr. With $M_V = -14.1$ mag currently (O'Connell et al. 1994), the evolved cluster will dim to $M_V = -7$ to -8 mag, again lying comfortably within the peak of the luminosity function of globular cluster systems ($\langle M_V \rangle \approx -7.3$ mag; Harris 1991). NGC 1569-A will have $M/L_V = 2.5$–6.3 $(M/L_V)_\odot$, comparable to and perhaps slightly larger than normal for Galactic globular clusters [0.7–2.9 $(M/L_V)_\odot$; Mandushev et al. 1991]. This finding implies that, to a first approximation, the stellar initial mass function of NGC 1569-A is similar to that of typical globular clusters.

4. CONCLUSIONS

We obtained high-dispersion optical spectra of one of the two luminous compact clusters (object "A") located in the central region of the dwarf galaxy NGC 1569. Cool supergiants contribute significantly to the light at visual wavelengths, and we argue that it is possible to measure the velocity dispersion of the cluster using a conventional cross-correlation technique. The velocity dispersion along the line of sight is estimated to be $\sigma_* = 15.7 \pm 1.5$ km s^{-1}. Combined with the size measurement known from *HST* images, a dynamical mass of $M = (3.3 \pm 0.5) \times 10^5\ M_\odot$ is determined using the virial theorem. The derived mass, mass density, and probable mass-to-light ratio of NGC 1569-A provide compelling evidence that the cluster will evolve into a fairly massive globular cluster. Further observations of this kind are needed to establish whether other luminous, compact, young star clusters being discovered in starburst environments are similar in nature to NGC 1569-A.

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