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The dynamics of the globular cluster M22 (NGC 6656)†

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Abstract. We have used the Hubble Space Telescope (HST) observations to measure proper motion of the globular cluster NGC 6656 (M22) with respect to the background bulge stars and its internal velocity dispersion profile. Based on the proper motion of the clusters, its space velocity and orbit are also calculated. The central velocity dispersion in radial and tangential components of the internal motion of cluster stars is 16.99 km s^{-1}. We derive the mass-to-light ratio $M/L_V \sim 3.3 \pm 0.2$ which is relatively higher than the previous works.

Keywords. astrometry — proper motion — globular clusters: dynamics — globular clusters: individual: NGC 6656(M22)

1. Introduction

NGC6656 (M22) is one of the nearest globular clusters from the Sun, being about 3 kpc distant (Peterson & Cudworth 1994; Harris 2003). With the HST WFPC2 having been on work for about ten years, much progress has been made in recent years in the study of some globular clusters and we can now combine high-resolution images over a sufficiently long time baseline to measure proper motions of the nearby globular clusters.

The globular cluster NGC 6656 ($\alpha = 18^{\mathrm{h}}36^{\mathrm{m}}24^{\mathrm{s}}.2$, $\delta = -23°54'12''$, $l = 9°.89$, $b = -7°.55$) is a moderately concentrated one — the core radius of $1'.42$ and central concentration of $c = 1.31$ (Trager, Djorgovski & King 1993). Its central surface brightness $\mu_v = 17.32$ mag arcsec^{-2} (Harris 2003). The metallicity of this cluster is rather low ([Fe/H] = –1.62±0.08; Richter, Hilker & Richtler 1999). It should belong to the population of "halo" clusters (Zinn 1985). The cluster appears somewhat elongated on the sky: White & Shawl (1987) found an axial ratio of 0.86 ±0.01 and a position angle of 139°±2° for the major axis.

There is a small spread in [Fe/H] of the stars of NGC 6656 (Pilachowski *et al.* 1982), where [Fe/H] correlates positively with CN and CH band strengths (Lehnert, Bell & Cohen 1991). Among galactic globular clusters, this property is shared only by ω Cen. However, some new research (Monaco *et al.* 2004; Ivans *et al.* 2004) show some evidence that differential reddening may bring on the metallicity spread. Kinematics is also unusual. Peterson & Cudworth (1994) find there is some rotation in the clusters and its mass-to-light ratio is about 0.96, being the lowest one from the galactic globular cluster measured to date. It is not clear whether these various anomalies mean that NGC 6656 is indeed an unusual cluster, or simply, poorly studied. In any case, a more detailed understanding of its dynamics would appear to be important.

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2. Observations and reductions

Our proper motions are based on data of three epoch observations taken with Wide Field Planetary Camera 2 (WFPC2) aboard the HST. The first epoch data consist of four frames taken as part of program GO 5404 on 7 April 1994 through the F502N filter. The second epoch data are taken by program GO 7615 from 22 February to 15 June 1999 through F814W and F606W filter. This program also took a few frames in February 2000, which provide an additional epoch data that strengthen the proper-motion measurements.

The data frames were initially put through the standard HST on-the-fly calibration pipeline, which involves bias and dark subtraction and flat-field correction. The preliminary star lists were got under the DAOPHOT, and then all the frames were reduced by the methods of Anderson & King (2000). We use the images of stars observed in multiple ($\geqslant$4) frames to determine the effective point-spread function. The 34-row error and distortion were also corrected using the results of Anderson & King (1999, 2003). We transferred all corrected positions into a reference frame by polynomial transformations including quadratic terms to eliminate the possible tilt or so. We used the relatively bright stars that exist in all frames as the matched referenced stars under the help of the 2MASS catalogues and the task METRIC.

Thanks to the good overlap of all epoch frames, we have enough stars in each CCD field that it is not necessary to combine different CCDs to obtain more stars. We just match the images of same CCD of all epochs. Taking a frame in 2000 as the reference, we then construct a matched star list and calculate the relative proper motions of stars in each CCD field.

3. Analyses and results

3.1. *Proper motion*

Since the projected celestial coordinates of NGC 6656 are very close to the Galactic Center, it is reasonable to suppose the field stars mainly belong to the bulge.

By means of the Gaussian fit along the RA and Dec axis, respectively, we obtained the relative proper motion of NGC 6656 with respect to the bulge of $\mu_\alpha \cos\delta = 10.19 \pm 0.20\,\mathrm{mas\,yr^{-1}}$ and $\mu_\delta = -3.34 \pm 0.10\,\mathrm{mas\,yr^{-1}}$. Giving the radial velocity of NGC 6656, $V_r = -148.9 \pm 0.4\,\mathrm{km\,s^{-1}}$ (Harris 2003) and the Sun motion of $(U_\odot, V_\odot, W_\odot) = (10, 15, 8)\,\mathrm{km\,s^{-1}}$ (Dauphole et al. 1998), the rotational velocity of the Local Standard of Rest of $V_{LSR} = 220\,\mathrm{km\,s^{-1}}$ and the solar distance to the Galactic Center 8.0 kpc (Dinescu, Girard van Altena 1999), and the cluster distance $d = 3.2 \pm 0.3$ kpc from the Harris' (2003) catalog of clusters, we got the three components of space velocity for NGC 6656 with respect to the bulge: $(\Pi, \Theta, W) = (184 \pm 3, 209 \pm 14, 132 \pm 15)\,\mathrm{km\,s^{-1}}$. Errors in velocities include the uncertainty in the proper motions, radial velocities, and the distance of the cluster.

Compared to the previous work (Dinescu, Girard & van Altena 1999), few differences were found. It may be suggested that the motion of bulge in the field is low and we could try to calculate the galactic orbit of the cluster based on our proper motion uncorrected for the motion of bulge stars. Combining this result with the potential function of the Milk Way given by Allen & Santillan (1991) which is the superposition of the potential functions of the central mass point, ellipsoidal disk and spherical halo, we compute the orbit of NGC 6656 in the past 10 Gyr. We found the orbit of NGC 6656 has a moderate eccentricity and a relatively lower obliquity, and the cluster is near its perigalacticon now. It is a proof by kinematics that NGC 6656 belongs to the halo population according to the classification by Zinn (1985), but the frequent interactions with the disk may reasonably change its orbit, resulting in a low concentration for such a high mass cluster, and elongate it.

3.2. *Velocity dispersion profile of the cluster stars*

We use the cluster stars defined above to investigate the internal velocity dispersion profile of the cluster. First, we transform the proper motions into radial and tangential components with respect to the radius vector from the cluster center, which is given by Harris (2003), to each star. Second, we binned the stars into equal number bins (200 stars per bin) and use a maximum likelihood technique similar to the methods of Drukier *et al.* (2003) to estimate the dispersion in each bin using the following equation for the likelihood function

$$L(v_i|\bar{v}, \sigma_r, \epsilon_i) = (1/\sqrt{2\pi(\epsilon_i^2 + \sigma_r^2)})\exp[-(v_i - \bar{v})^2/2(\epsilon_i^2 + \sigma_r^2)]$$

and we calculate the total mass of the cluster Mcl using the following equation,

$$M_{cl} = \frac{9}{2\pi G}\frac{\mu r_c \sigma_p^2(0)}{\alpha p}$$

where values of μ, α and p were connected with the concentration parameters and tabulated by King (1966) and Peterson & King (1975), and adopting the surface brightness profile parameters of Trager, Djorgovski & King (1995), we then compute the ratio of total mass to V-band luminosity of $M/L_V = 3.13$. If we alternatively use the formula of Illingworth(1976) for the cluster mass: $M = 167 r_c \mu \sigma_0^2$, adopting the V-magnitudes and distance modulus given by Harris (2003), $A_V = 3.2E(B-V)$ (Da Costa & Armandroff 1990), the corresponding values for M/L_V is 3.5.

We conclude that a resonable representation of the M/L_V of M22 is 3.3 ± 0.2, which is larger than the result of Peterson & Cudworth (0.85 ± 0.15; 1994) and twice the typical values of the core of galactic globular clusters (McLaughlin 2000). Considered the old data of distance modulus and the stars, which are mainly outer bright stars of the cluster used in the work of Peterson & Cudworth (1994), our new M/L ratio is more reasonable and NGC 6656 may not be the lowest M/L globular cluster. Perhaps,the high mass-to-light ratio suggests that this cluster may contain dark mass or a larger number of faint objects.

The correlations of cluster velocity dispersions, σ, with surface brightness $\sum_0$ have been discussed by Djorgovski & Meylan (1994). They find the core radii and concentrations play the roles of a "second parameter" in these correlations. The new bivariate correlations fitted by Djorgovski (1995) represent the views of the fundermental plane (FP) of GCs edge-on:

$\sum_V(0) = (-4.9 \pm 0.2)(\log\sigma - 0.45\log r_c) + (20.45 \pm 0.2)$

according to our σ results, the corresponding position of NGC 6656 on the Fig.1 of Djorgovski (1995) is slightly above the FP. The same result occurred when we turn to apply the analytic correlations predicted by King models: $5\log\sigma_0 + 2.5\log\mu r_c \sim -M_V$. Since the relatively low concentration and high luminosity of NGC6656, this work may help to enhance the sample of the "bright" end of FP.

4. Summary and discussion

Using three epoch WFPC2 images, we measured the relative proper motion of NGC 6656 with respect to the bulge and the internal velocity dispersion of the cluster. Combining the result of proper motion with the motion of Sun, rotation of Local Standard of Rest and radial velocity of clusters, we derived the 3-dimensional motion of cluster. Given the gravitational potential function of our Galaxy, the orbit of the cluster during the past 10 Gyr was calculated. From the results we found, NGC 6656 has a moderate eccentricity and relatively lower obliquity orbit and is near its perigalacticon now. Our work on the cluster stars suggests that the velocity dispersion in the core radius is larger than the dispersion measured early along the line of sight. Adopting the new fundamental parameters of cluster, we calculate the M/L ratio of the cluster and found the value about 3.3 which is higher than the previous work. We adopt our result to test the FP relation of the globular clusters. A little deviation is found. More observations are needed to confirm the results presented here: longer time baseline can further improve the precision of the proper motion; a larger field will contain more cluster and field stars to give a more distinct separation.

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