THE ROTATION OF SUBPOPULATIONS IN $\omega$ CENTAURI

E. Pancino, A. Galf, F. R. Ferraro, and M. Bellazzini

Received 2007 March 1; accepted 2007 April 19; published 2007 May 8

ABSTRACT

We present the first result of the Ital-FLAMES survey of red giant branch (RGB) stars in $\omega$ Cen. Radial velocities with a precision of $\sim 0.5$ km s$^{-1}$ are presented for 650 members of $\omega$ Cen observed with FLAMES-GIRAFFE at the Very Large Telescope. We found that stars belonging to the metal-poor (RGB-MP), metal-intermediate (RGB-MInt), and metal-rich (RGB-a) subpopulations of $\omega$ Cen are all compatible with having the same rotational pattern. Our results appear to contradict past findings by Norris et al., who could not detect any rotational signature for metal-rich stars. The slightly higher precision of the present measurements and the much larger sample size, especially for the stars richer in metals, appear as the most likely explanations for this discrepancy. The result presented here weakens the body of evidence in favor of a merger event in the past history of $\omega$ Cen.

Subject headings: globular clusters: individual (NGC 5139) techniques: radial velocities

Online material: machine-readable table

1. INTRODUCTION

The giant globular cluster (GC) $\omega$ Centauri is one of the most studied objects in the Milky Way since the 1960s, thanks to its many peculiar properties. As its main anomaly, $\omega$ Cen shows a wide abundance spread ($\sim$1 dex) not only in the light elements but also in the iron-peak elements (Norris & Da Costa 1995; Norris et al. 1996; Sunzette & Kraft 1996; Smith et al. 2000), pointing toward a chemical evolution history more reminiscent of a dwarf galaxy than a genuine GC. Moreover, its structural, kinematical, and dynamical properties appear atypical for a Galactic GC, having properties more similar to dwarf elliptical galactic nuclei (Mackey & van den Bergh 2005) and being also an elongated (Geyer et al. 1983; Pancino et al. 2003), rotating system (Merritt et al. 1997) that is not completely relaxed dynamically (Anderson 1997; Ferraro et al. 2006).

Among the most recent, puzzling results, we list the detection of complex substructures in all evolutionary sequences, including the red giant branch (RGB; Lee et al. 1999; Pancino et al. 2000; Sollima et al. 2005a), the subgiant branch and turnoff region (Ferraro et al. 2004; Sollima et al. 2005b), and the main sequence (Bedin et al. 2004; Piotto et al. 2005). These studies have raised new questions that need to be answered, such as the debated age differences among subpopulations (Hilker & Richtler 2000; Hughes & Wallerstein 2000; Sollima et al. 2005b), the possibility of complex substructures in all evolutionary sequences, including the red giant branch (RGB; Lee et al. 1999; Pancino et al. 2000; Sollima et al. 2005a), the subgiant branch and turnoff region (Ferraro et al. 2004; Sollima et al. 2005b), and the main sequence (Bedin et al. 2004; Piotto et al. 2005). Among the stars in the cluster were divided into two groups based on their Ca abundance. They showed that stars poorer in metals rotate the same as the majority of stars in the cluster do, while stars richer in metals do not show any sign of rotation. They also showed that the radial velocity dispersion appears to decrease with metallicity, a very strange behavior since stars richer in metals tend to be concentrated in the cluster center, which is dynamically hotter.

2. OBSERVATIONS AND DATA TREATMENT

A sample of $\sim$700 red giants was selected from the wide field photometry originally published by Pancino et al. (2000) and Pancino (2003) to derive accurate chemical abundances of stars spanning the whole metallicity range of $\omega$ Cen. Special care was taken to include a large fraction of high-metallicity stars, which are the least studied up to now. All program stars are distributed within 15" from the cluster center. Figure 1 shows the program stars, marked on the B versus $(B-I)$ color-magnitude diagram (CMD) of Pancino et al. (2000). Following the classification scheme of Pancino et al. (2000, 2003), we divide the stars into three groups: the metal-poor population (RGB-MP) comprising 75% of the cluster giants, with $[\text{Fe/H}] \sim -1.6$; the metal-intermediate population (RGB-MInt) comprising 20% of the cluster giants, with $[\text{Fe/H}] \sim -1.2$; and the metal-rich or anomalous stars (RGB-a) comprising 5% of the cluster giants, with $[\text{Fe/H}] \sim -0.6$ (Pancino et al. 2002). Sample sizes are shown in Table 2 below.

Observations were done with FLAMES (Pasquini et al. 2002) at the ESO VLT in Paranal, Chile, between 2003 May 22 and 28, within the Guaranteed Observing Time of the Ital-FLAMES Consortium. FLAMES was used in Medusa-combined mode, feeding 8 fibers to UVES and 132 fibers to GIRAFFE. To ensure the maximum homogeneity in data quality and treatment, here we present the first results obtained with GIRAFFE only, using the high-resolution ($R = 22,500$) grating HR13 (6120–6395 Å) and reaching a signal-to-noise ratio of $\sim$50–100 pixel$^{-1}$, depending on the star magnitude.

Data were reduced with the GIRAFFE BLDRS (Base-Line Data Reduction Software), which includes cosmic-ray removal, bias subtraction, flat-field correction, wavelength calibration, and pixel resampling. The version of the pipeline that we used does not include interorder background or sky subtraction, but these have no significant effect on radial velocity determinations.

Radial velocities were determined using DAOspec (P. B. Stetson & E. Pancino, 2007, in preparation), a program that automatically measures equivalent widths of absorption lines.

---

1 Based on data obtained with the Giraffe-FLAMES facility of ESO Very Large Telescope during the Ital-FLAMES GTO program 71.D-0217(A). Also based on data from the VALD and GESIAs databases.

2 INAF–Bologna Observatory, via Ranzani 1, I-40127 Bologna, Italy; elena.pancino@oabo.inaf.it.

3 Astronomy Department, Bologna University, via Ranzani 1, I-40127 Bologna, Italy.

4 Available at http://girbldrs.sourceforge.net.

5 Available at http://cadwww.hia.nrc.ca/stetson/daospec/ and http://www.bo.astro.it/~pancino/projects/daospec.html.
correction is less than a common zero point to our observed velocities. The typicalicture Atmospheriques; Jaquinet-Husson et al. 2003) database to find offsets, up to 3 km s\(^{-1}\) of the order of 0.13 km s\(^{-1}\). Where

\[ n \]

of the most common species obtained from the VALD\(^6\) (Vienna Atomic Line Database; Kupka et al. 1999). Observed radial velocities are the average of the velocity obtained for each line after a 3 \(\sigma\) clipping, and the associated uncertainty is \(\sigma/\sqrt{n}\), where \(n\) is the number of lines used. Typical uncertainties are of the order of 0.13 km s\(^{-1}\).

Since radial velocities were not the main goal of the observing program, simultaneous calibration lamps were not taken during the observations. We used laboratory wavelengths of the telluric lines of the 6300 Å O\(_2\) absorption band from the GEISA\(^7\) (Gestion et Etude des Informations Spectroscopique Atmospheriques; Jaquinet-Husson et al. 2003) database to find a common zero point to our observed velocities. The typical correction is less than ±1 km s\(^{-1}\), with an uncertainty of ~0.45 km s\(^{-1}\), but we found that for some exposures there were larger offsets, up to 3 km s\(^{-1}\). Finally, we applied the heliocentric correction using the \texttt{rvcorrect} task within IRAF.\(^8\) The resulting heliocentric radial velocities have a typical uncertainty of 0.5 km s\(^{-1}\) and are reported in Table 1.

Contaminating field stars were easily eliminated since their average velocity is −4.0 ± 38.5 km s\(^{-1}\), in very good agreement with Galactic model predictions for disk stars (Robin et al. 2003) and very different from the typical velocity of \(\omega\) Cen. After removing all stars with \(V_r < 190\) km s\(^{-1}\), the final sample contains 649 cluster members, with an average \(V_r = 233.4\) and \(\sigma = 13.2\) km s\(^{-1}\). Star by star comparisons with other catalogs yield a very good agreement. For instance, the average radial velocity difference of the 136 stars in common with Mayor et al. (1997) is \(\Delta V_r = 0.4 ± 1.4\) km s\(^{-1}\), while for the 53 stars in common with Suntzeff & Kraft (1996) it is \(\Delta V_r = 0.5 ± 1.8\) km s\(^{-1}\), and for the 382 stars in common with Reijns et al. (2006) it is \(\Delta V_r = 2.4 ± 4.6\) km s\(^{-1}\).  

3. RESULTS

We used the photometric definition of populations described in § 2, together with our radial velocity measurements, to construct rotation curves for subpopulations in \(\omega\) Centauri. To this aim, we first deprojected right ascension and declination into X’ and Y’-coordinates with the following relations (see also van de Ven et al. 2006), suited for extended objects that are not close to the celestial equator:

\[ X' = -r_0 \cos \delta \sin (\alpha - \alpha_0), \]

\[ Y' = r_0 [\sin \delta \cos \delta_0 - \cos \delta \sin \delta_0 \cos (\alpha - \alpha_0)], \]

where \(r_0 = 10,800/\pi\) is the scale factor to have \(X'\) and \(Y'\) in arcminutes.

As a second step, we searched for the orientation of the rotation axis \(\theta\) that maximizes the amplitude of the rotation signal. We found a relatively broad maximum around \(\theta = 0\), and thus, for simplicity, we adopt a rotation axis aligned with the north-south direction, which corresponds to the Y’ axis and to the minor isophotal axis (Geyer et al. 1983; Pancino et al. 2003). We therefore plotted radial velocities of each subpopulation against \(X'\) (Fig. 2) and found a clear signature of rotation not only for the RGB-MP, as was expected, but also for the RGB-MInt and the RGB-a. The numbers of stars in the four quadrants of each rotation curve show that the rotational signature is strong even for the most sparse population, i.e., the

\[ ^{6} \text{Available at http://www.astro.uu.se/~vald/}. \]

\[ ^{7} \text{Available at http://ara.lmd.polytechnique.fr/htdocs-public/products/GEISA/HTML-GEISA/}. \]

\[ ^{8} \text{The Image Reduction and Analysis Facility is distributed by the National Optical Astronomy Observatories, which is operated by the association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.} \]

**TABLE 1**

| WFI\(^a\) | R.A. \(^b\) (deg) | Decl. \(^b\) (deg) | \(B^*\) (mag) | \(I^*\) (mag) | \(V_r\) (km s\(^{-1}\)) | \(\sigma V_r\) (km s\(^{-1}\)) | Pop. \(^c\) |
|---|---|---|---|---|---|---|---|
| 100981| 201.8168600| −47.5958400| 13.202| 10.478| 247.377| 0.226| 1|
| 102141| 201.9786400| −47.5883400| 14.508| 12.360| 237.910| 0.382| 1|
| 102342| 201.8439800| −47.5879700| 14.525| 12.251| 238.894| 0.197| 1|
| 103979| 201.8236700| −47.577500| 14.428| 12.251| 234.816| 0.781| 2|
| 104113| 201.8308800| −47.569700| 15.345| 13.315| 239.967| 0.382| 1|

**Note.**—Table 1 is published in its entirety in the electronic edition of the *Astrophysical Journal.* A portion is shown here for guidance regarding its form and content.

\(^{a}\) WFI star numbers and \(B, I\) magnitudes from Pancino et al. (2000).

\(^{b}\) Coordinates obtained using the astrometric catalog by van Leeuwen et al. (2000).

\(^{c}\) Population classification according to Pancino et al. (2000, 2003); 1 stands for RGB-MP, 2 for RGB-MInt, and 3 for RGB-a (see text for details).
Norris et al. (1996) with the radial velocity measurements by et al. (1997) correlated the calcium IR triplet abundances by the center (see Table 2). As can be seen, the values of Ven et al. 2006) as the average of between 6 near the maximum (as found by Merritt et al. 1997; van de RGB-a. Assuming that the rotation curves are symmetrical to the western side. More quantitatively, the probabilities being extracted from the same parent distribution as the western half (see Fig. 2). A Kolmogorov-Smirnov test velocities on the eastern half of the cluster would be identical compatible with previous literature estimates. The size of the entire sample is not so different: Norris et al. (1997) except that the dispersion increases again for the most metal-rich stars in their sample.

Velocity dispersions may be quite sensitive to outliers and to the radial distribution of the chosen samples, and a detailed analysis would greatly benefit from the metallicity estimates of individual stars that are not yet available. Here we simply note that there appears to be no difference in the global velocity dispersions of the three subsamples (Table 2). However, the present photometric classification is probably too coarse to reveal subtle effects such as the ones presented by Norris et al. (1997) and Sollima et al. (2005b); hence, we postpone any conclusion on radial velocity dispersions to a future paper. On the other hand, strong coordinate motions like the rotation patterns shown in Figure 2 are clearly very robust to the effect of a few outliers and can be profitably studied with the available information. Even in the absence of individual metallicity estimates, Figure 2 leaves very little room for a nonrotating subpopulation within ω Cen. To facilitate a comparison with Figure 3 of Norris et al. (1997), Figure 3 shows the run of $V$ with the position angle (P.A.) for the three populations of ω Cen. As before, all populations show the well-known rotation along the east-west direction (Norris et al. 1997; Merritt et al. 1997). Even the RGB-a, despite the smaller sample, is still compatible with the same rotational pattern. The amplitude $A_{\text{rot}}$ of the rotation signal in Figure 3, obtained with a $\chi^2$ minimization, is reported in Table 2. However, $A_{\text{rot}}$ can only be considered as an indicative value since it contains contributions from stars at very different radii, and the systemic rotation is highly radius-dependent.

We considered two possible reasons why the rotational signature was not found before: sample size and measurement precision. The size of the entire sample is not so different: Norris et al. (1997) had ~400 stars, we have ~650. However, our sample

### TABLE 2

| Population     | $n$  | $V_r$ (km s$^{-1}$) | $\sigma_r$ (km s$^{-1}$) | $A_{\text{rot}}$ (km s$^{-1}$) | $V_{\text{rot}}$ (6°–8°) (km s$^{-1}$) | $n$ (6°–8°) |
|----------------|-----|---------------------|--------------------------|-------------------------------|---------------------------------------|-------------|
| Whole sample   | 649 | 233.4               | 13.2                     | ~6.8 ± 1.0                    | 87                                    |
| RGB-MP         | 313 | 232.5               | 13.3                     | ~7.1 ± 1.5                    | 46                                    |
| RGB-MInt       | 266 | 234.2               | 13.1                     | ~6.3 ± 1.7                    | 33                                    |
| RGB-a          | 70  | 234.0               | 13.4                     | ~6.0 ± 3.0                    | 8                                     |

9. This was referred to as the radial velocity dispersion paradox in ω Cen, and a possible explanation, involving the presence of a face-on metal-rich disk, was presented by van den Bosch et al. (1999). Some support for this hypothesis comes from the possible presence of a small disklike structure in the center of ω Cen that was pointed out by van de Ven et al. (2006).

10. As stated before, the data presented in this Letter do not allow us to reach a firm conclusion on the velocity dispersion, so we will only consider the rotation patterns in the following discussion.
that is only slightly higher and still below 1 km s\(^{-1}\), although we have an uncertainty of \(\sim 0.5\) km s\(^{-1}\) (Merritt et al. 1997) are overplotted for reference.

Fig. 3.—Radial velocity measurements plotted against the P.A. (counted from north toward east) for the RGB-MP (top panel), the RGB-MInt (middle panel), and the RGB-a (bottom panel). Sinusoids with an amplitude of \(\sim 8\) km s\(^{-1}\) (Norris et al. 1997) are overplotted for reference.

contains more metal-rich stars: we have 313 stars in the RGB-MP, and 336 stars in the RGB-MInt and RGB-a together, while Norris et al. (1997) had \(\sim 300\) metal-poor stars and less than 100 metal-rich stars. Also, the precision of the radial velocity measurements could play a role, although we have an uncertainty of \(\sim 0.5\) km s\(^{-1}\), and Mayor et al. (1997) have an uncertainty that is only slightly higher and still below 1 km s\(^{-1}\). However, as Norris et al. (1997) made clear, the absence of rotation for the metal-rich group was confirmed only at the 2 \(\sigma\) level; therefore, the combination of a slightly higher precision and a much larger sample size are probably enough to explain why we were able to reveal such a signature with our data set.

4. CONCLUSIONS

We presented the first results from the Ital-FLAMES survey of the RGB of \(\omega\) Cen. Radial velocities with uncertainties of 0.5 km s\(^{-1}\) are derived for 650 radial velocity members of \(\omega\) Cen and are in very good agreement with previous literature measurements. The main result obtained is that all three sub-populations of \(\omega\) Cen show the same rotation pattern. These findings appear in contradiction with the results presented by Norris et al. (1997). We show that a combination of higher precision in the \(V_r\) measurements and of a larger sample size, especially for metal-rich stars (RGB-MInt and RGB-a), is the most likely cause for the discrepancy.

The results by Norris et al. (1997) were the main piece of evidence in support of a merger event in the past evolution of \(\omega\) Cen. The evidence presented here suggests that there is no rotational anomaly in \(\omega\) Centauri. The only other remaining evidence, apart from the radial velocity dispersion paradox mentioned above, that still points toward a complicated dynamical history is the structural difference among populations found by Pancino et al. (2003) and the somewhat debated differential proper motion for the RGB-a found by Ferraro et al. (2002), questioned by Platais et al. (2003), but supported by Hughes et al. (2004). Clearly, a deeper investigation into these aspects is now needed to finally settle the issue.

We thank P. B. Stetson, A. Sollima, and C. Cacciari. We also thank J. E. Norris, the referee of this Letter, for his constructive comments. The financial support from the PRIN-INAF 2005, PRIN-INAF2006, and ASI-INAF I/023/05/0 grants is acknowledged.

REFERENCES

Anderson, J., 1997, Ph.D. thesis, Univ. California, Berkeley
Bedin, L. R., Piotto, G., Anderson, J., Cassisi, S., King, I. R., Momany, Y., & Carraro, G. 2004, ApJ, 605, L125
Ferraro, F. R., Bellazzini, M., & Pancino, E. 2002, ApJ, 573, L95
Ferraro, F. R., Sollima, A., Pancino, E., Bellazzini, M., Straniero, O., Origlia, L., & Cool, A. M. 2004, ApJ, 603, L81
Ferraro, F. R., Sollima, A., Rood, R. T., Origlia, L., Pancino, E., & Bellazzini, M. 2006, ApJ, 638, 433
Geyer, E. H., Nelles, B., & Hopp, U. 1983, A&A, 125, 359
Hilker, M., & Richtler, T. 2000, A&A, 362, 895
Hughes, J., & Wallerstein, G. 2000, AJ, 119, 1225
Hughes, J., Wallerstein, G., van Leeuwen, F., & Hilker, M. 2004, AJ, 127, 980
Jaquinet-Husson, N., Scott, N. A., Chedin, A., & Chursin, A. A. 2003, Atmos. Oceanic Opt., 3, 256
Kupka, F., Piskunov, N., Ryabchikova, T. A., Stempels, H. C., & Weiss, W. W. 1999, A&AS, 138, 119
Lee, Y.-W., Joo, J.-M., Sohn, Y.-J., Rey, S.-C., Lee, H.-C., & Walker, A. R. 1999, Nature, 402, 55
Mackey, A. D., & van den Bergh, S. 2005, MNRA, 360, 631
Mayor, M., et al. 1997, AJ, 114, 1087
Merritt, D., Meylan, G., & Mayor, M. 1997, AJ, 114, 1074
Norris, J. E. 2004, ApJ, 612, L25
Norris, J. E., & Da Costa, G. S. 1995, ApJ, 447, 680
Norris, J. E., Freeman, K. C., & Seitzer, P. 1997, ApJ, 487, L187
Norris, J. E., Freeman, K. C., & Mihlaga, K. J. 1996, ApJ, 462, 241
Pancino, E. 2003, Ph.D. thesis, Bologna Univ.
Pancino, E., Ferraro, F. R., Bellazzini, M., Piotto, G., & Zoccali, M. 2000, ApJ, 534, L83
Pancino, E., Pasquini, L., Hill, V., Ferraro, F. R., & Bellazzini, M. 2002, ApJ, 568, L101
Pancino, E., Seleznev, A., Ferraro, F. R., Bellazzini, M., & Piotto, G. 2003, MNRAS, 345, 683
Pasquini, L. et al. 2002, Messenger, 110, 1
Piotto, G., et al. 2005, ApJ, 621, 777
Platais, I., Wyse, R. F. G., Hebb, L., Lee, Y.-W., & Rey, S.-C. 2003, ApJ, 591, L127
Reijns, R. A., Seitzer, P., Arnold, R., Freeman, K. C., Ingerson, T., van den Bosch, R. C. E., van de Ven, G., & de Zeeuw, P. T. 2006, A&A, 445, 503
Robin, A. C., Reylé, C., Derrière, S., & Picaud, S. 2003, A&A, 409, 523
Smith, V. V., Suntzeff, N. B., Cunha, K., Gallino, R., Busso, M., Lambert, D. L., & Straniero, O. 2000, AJ, 119, 1239
Sollima, A., Ferraro, F. R., Pancino, E., & Bellazzini, M. 2005a, MNRAS, 357, 265
Sollima, A., Pancino, E., Ferraro, F. R., Bellazzini, M., Straniero, O., & Pasquini, L. 2005b, ApJ, 634, 332
Suntzeff, N. B., & Kraft, R. P. 1996, AJ, 111, 1913
van der Bosch, R. C. E., van de Ven, G., & de Zeeuw, P. T. 2006, A&A, 445, 513
van Leeuwen, F., Le Poole, R. S., Reijns, R. A., Freeman, K. C., & de Zeeuw, P. T. 2000, A&A, 360, 472