Two Cannonballs Shot Out from the Core of the Globular Cluster 47 Tucanae

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I. Introduction

In dynamics of globular clusters, the worst problem is by far their dynamical evolution, which turns out to be unstable. During the past decade, an important observational and theoretical activity related to the problem of core collapse has partly changed and greatly improved our theoretical understanding of the dynamical evolution of globular clusters (see the proceedings of the ASP Conference on Formation and Evolution of Star Clusters, ed. Janes, 1991, and references therein).

There are at least three different ways to look at the dynamical evolution of a globular cluster towards gravitational instability, an evolution characterized, during most of the life of the cluster, by a slow contraction of its core and an equally slow expansion of its envelope. First, relaxation through encounters ejects stars from the core and causes the cluster central part to contract, since its binding energy is shared among fewer stars. The contraction speeds up the relaxation and the whole thing runs away (Spitzer and Härm, 1958, *Ap. J.* **127,** 544). Second, with two populations in equipartition, if the total mass M_2 of the heavier stars is sufficiently large compared to the total mass M_1 of the lighter stars, there is no equilibrium distribution of heavy stars in which v_2 is much less than v_1. Then, if m_1 and m_2 are the individual masses of the lighter and heavier stars, respectively, then $M_2/M_1(m_2/m_1)^{3/2}$ must be less than 0.16 for equilibrium (Spitzer, 1969, *Ap.J.L.* **158,** L139). When violated, this criterion indicates that the large self-gravitation of the heavier stars drives them into a high-temperature sub-system in the core of the cluster. Third, beyond a certain concentration – $\varrho_{\rm core} \geq 709\ \varrho_{\rm halo}$ – the system is subject to the remarkable gravothermal instability, consequence of the negative specific heat of a self-gravitating stellar system. The core of the cluster can no longer stay in equilibrium with the envelope. It makes a thermodynamic turnabout, the energy flows the wrong way and the centre of the cluster collapses (Antonov, 1962, for an English translation see IAU Symp. 113, 1985, p. 525; Lynden-Bell and Wood, 1968, *M.N.R.A.S.* **135,** 495).

The essential conclusion which can be drawn from theoretical works consists of expecting the core of an old cluster eventually to collapse, suffering what Lynden-Bell called the *gravothermal catastrophy.* If theoreticians have, for a long time, little doubt about core collapse, the situation has been less clear observationally. From the survey concerning about 110 galactic globular clusters (Djorgovski and King, 1986, *Ap.J.L.* **305,** L61), it is established that 20% of them have surface brightness profiles which are not easily fitted by King-Michie multimass anisotropic dynamical models. Part of these problems may be the result of the discrete nature of the core of such high-concentration clusters, whose light is dominated by the contribution of a few (less than ten) bright stars. Recent observations with the Hubble Space Telescope failed to display the expected central casp in the core of M15 (Lauer et al., 1991, *Ap.J.L.* **369,** L45), and in NGC 6397 as well. This could be explained by recent theoretical simulations (Chernoff and Weinberg, 1990, *Ap.J.* **351,** 121) which show that the changes in the cluster during deep core collapse could be largely invisible, i.e., not strongly impressed on the luminosity profile. These authors show that high-concentration King-Michie

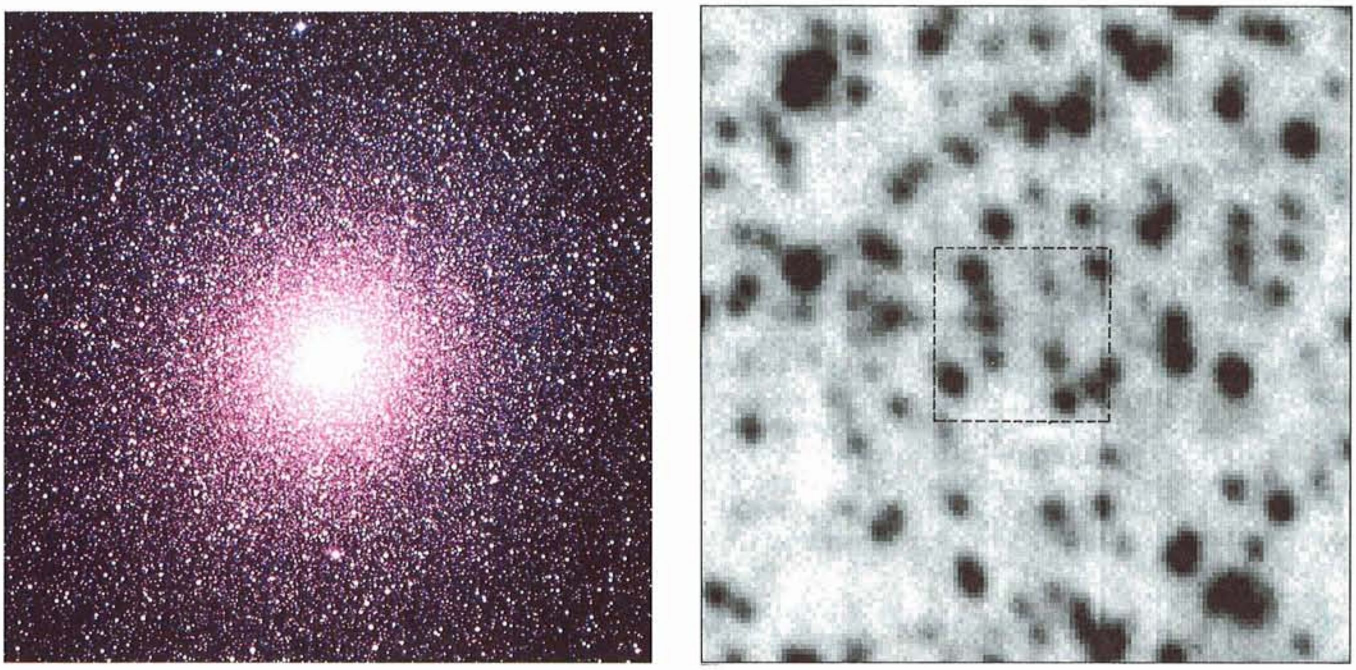

Figure 1: *(a) Composite photograph of 47 Tucanae obtained from three ESO Schmidt plates centred on different wavelengths (3850 Å, 4950 Å and 6300 Å), taken by H.E. Schuster at La Silla, Chile, and processed by the ESO photographic laboratory in Garching bei München, Germany. (b) Enlarged chart of the innermost area of 47 Tuc. The dashed square represents the 6″ × 6″ sampling area. North is up and east to the left.*

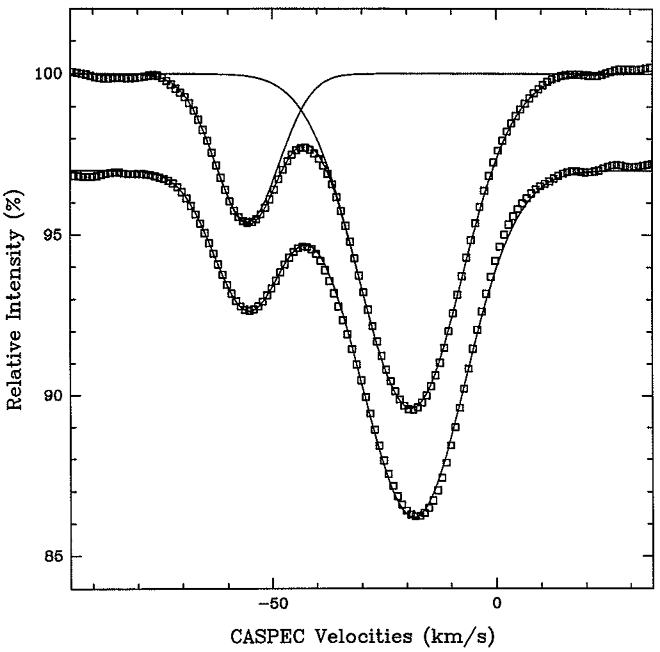

Figure 2: *Cross-correlation functions (CCFs) from the two integrated light spectra obtained in the core of 47 Tuc (one curve has been vertically shifted by 3% for clarity). The squares represent the CCFs themselves, the continuous lines the fitted functions which are combinations of two gaussians.*

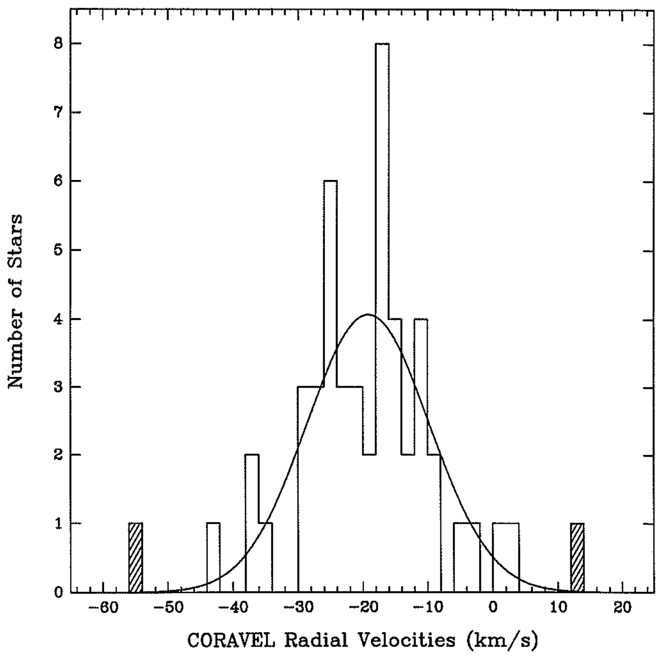

Figure 3: *CORAVEL radial velocity histogram of 50 stars located within the central arcminute of 47 Tuc, including the high-velocity star found in CASPEC spectra.*

models produce good fits not only during the early long phase of slow pre-collapse evolution of the cluster, but also during the late core-collapse phase. During the increase of central density, the visible stars do not follow the total density profile, but have much flatter profiles.

Actually, the gravothermal catastrophy does not look as catastrophic as it sounds! Since the seminal paper by Hénon (1961, *Ann. d'Astrophys.* **24,** 369), it is known that primordial binaries may delay the core collapse, and that, later during the collapse, because of the high increase in stellar density, binaries formed in the core are able to stop this collapse and even to trigger the re-expansion of the core, driving the cluster through a series of gravothermal oscillations (Sugimoto and Bettwieser, 1983, *M.N.R.A.S.* **204,** 19 p). Including in their model a term to represent the input energy from binaries, they found that after collapse, instead of decreasing monotonically, the central density undergoes nonlinear oscillations spanning several orders of magnitude. They suggested that many galactic globular clusters are at present undergoing just such gravothermal oscillations, the core spending the vast majority of the time in the expanded state.

Considering the high concentration and short central relaxation time of 47 Tucanae, the fact that this cluster does not show any evidence for core collapse is interesting. This cluster has perhaps already suffered the consequences of the gravothermal catastrophy and lives presently in the expanded phase between two consecutive contractions. The possible advanced stage of the dynamical evolution of this cluster may perhaps be unveiled through the observations of the characteristic and dynamics of individual stars. This southern globular cluster contains already an extremely rich zoo: one low-mass X-ray binary, about ten pulsars and a very high density of centrally clustered blue stragglers recently observed with the Hubble Space Telescope (Paresce et al. 1991, submitted to *Nature*).

As a contribution to the understanding of the dynamics of globular clusters, we undertake a survey dedicated to the measurement of the central velocity dispersion in the core of high-concentration galactic globular clusters (Dubath, Meylan, and Mayor, in preparation). The data concerning the core velocity dispersion from integrated light spectra in 47 Tuc and presented here are part of this survey. They are completed by a second determination of the velocity dispersion from mean radial velocities of about 50 stars located within one arcminute from the centre of the cluster.

II. Integrated Light Observations with CASPEC

The observations are integrated light spectra obtained in the core of 47 Tuc with CASPEC, the ESO Cassegrain Echelle Spectrograph, mounted on the 3.6-m telescope at La Silla, Chile. The CCD used is an RCA SID 503 high-resolution (ESO # 8). The instrument setup is standard, with the 31.6 line mm^{-1} grating and with a wavelength domain between 4250 and 5250 Å. We have two spectra obtained at an interval of two nights in July 1989. Both nights are characterized by strong winds and seeing values of the order of 2″ FWHM (recorded at the 1.54-m Danish telescope). The integration time is 15 minutes for both spectra, with a spectrum of a thorium-argon lamp taken before and after each exposure. The dimensions of the entrance slit are 1.4″ × 6.0″ for the first series of observations, and 1.2″ × 6.0″ for the second one. During the two exposures on the cluster core, a scanning of the nucleus was done with the entrance slit, in order to cover a zone of 6″ × 6″ and to avoid any problem of sampling which could occur by integrating only over a few bright stars. This sampling area is represented in Figure 1b by the dashed-line square of 6″ × 6″, superposed on a portion of a CCD image of the core of 47 Tuc, obtained by one of us at the ESO/MPI 2.2-m telescope at La Silla, with a standard B filter and 2 seconds of integration.

The spectra are reduced following standard procedures. No flat field operation is applied, since flux calibration is useless when cross-correlating spectra for obtaining radial velocity or velocity

Table 1: *Results from CASPEC and CORAVEL*

Instrument	$\bar{V}_r$ (cluster) (km s^{-1})	σ_p (core) (km s^{-1})	V_r (Caspec star) (km s^{-1})
CASPEC integrated light spectra within r = 3″			
6–7 July 1989	–18.4	8.8–9.2	–55.4 ± 0.2
8–9 July 1989	–19.1	9.1–9.3	–55.5 ± 0.2
CORAVEL measurements			
26–27 Dec. 1990	. . .	. . .	–54.3 ± 1.6
28–29 Dec. 1990	. . .	. . .	–55.5 ± 2.2

CASPEC and CORAVEL radial velocities and velocity dispersions concerning the 6″ × 6″ central area and the high-velocity star found in the CASPEC spectra.

dispersion. The reduced spectrum is then cross-correlated with a numerical mask. The properties of this mask, as well as the details of our cross-correlation technique, are described in a previous study concerning the Magellanic globular cluster NGC 1835 (Dubath, Meylan, and Mayor, 1990, *AA* **239,** 142). The mask used so far for optical cross-correlation with the spectrophotometer CORAVEL (COrrelation – RAdial – VELocities: Baranne, Mayor, and Poncet 1979, *Vistas in Astron.* **23,** 279) has been simply extended in order to cover the complete spectral domain of our CASPEC spectra, i.e., the interval from 4245 to 5275 Å. Our cross-correlation technique produces a cross-correlation function (CCF) which is nearly a perfect gaussian. Comparison with CCFs of standard stars displays the broadening of the cluster CCF, produced by the Doppler line broadening present in the integrated light spectra because of the random spatial motions of the stars. The quadratic difference in half-width at half-maximum gives a precise estimate of the stellar velocity dispersion in the sampled area of the globular cluster (Dubath et al. ibid).

III. Results from CASPEC Spectra

Figure 2 shows the CCFs – relative intensity as a function of the radial velocity – for the two spectra obtained in the core of 47 Tuc. The squares represent the CCFs themselves, the continuous lines the fitted functions which are combinations of two gaussians. The later are represented separately only in the case of the upper CCF. In a totally unexpected manner, both CCFs coming from two similar but independent spectra, exhibit an identical double dip. The deepest gaussian represents the light coming from the cluster as a whole, since it reproduces (V_r = –18.4 and –19.1 km s^{-1}, respectively, see Table 1) the systemic radial velocity of 47 Tuc known to be V_r = –18.8 ± 0.6 km s^{-1} from the radial velocities of 272 member stars (Meylan and Mayor, 1986, *AA* **166,** 122). This gaussian is also much broader than the mean CCF (stellar gaussian) defined as the mean of a set of CCFs from standard stars with late spectral types (Dubath, Meylan, and Mayor, in preparation). Consequently, the projected velocity dispersion σ_p in the core of 47 Tuc is derived, the two independent CCFs giving σ_p = 9.0 an 9.2 km s^{-1}, respectively (Table 1).

The second, less deep, gaussian corresponds to a radial velocity totally different from the systemic radial velocity of the cluster. Its width is much smaller and typical of CCFs coming from a single star. Therefore, we conclude that this second dip reveals the presence of a relatively bright star, inside the 6″ × 6″ sampling area, with a radial velocity value V_r = –55.5 km s^{-1} (V_r = –55.4 ± 0.2 and –55.5 ± 0.2 km s^{-1}, respectively from the upper and lower (CCF). Its radial velocity relative to the cluster is about four times larger than the velocity dispersion in the core of the cluster, i.e., V_r(star) – V_r(47Tuc) = –36.7 km s^{-1} with σ_p(core) = 9.1 km s^{-1}.

Challenged by this double dip, we were wondering which star in the sampling area (Figure 1b) was the interloper. We have unveiled at least part of the puzzle, by obtaining individual radial velocities for some of the brightest stars in the sampling area. These results, acquired in December 1990 by direct radial velocity measurements with CORAVEL mounted on the ESO 1.54-m Danish telescope at La Silla, Chile, allow to locate the high-velocity star. The CASPEC radial velocities are confirmed by two CORAVEL measurements which give V_r = –54.3 ± 1.6 km s^{-1} on 26-27 December 1990 and V_r = –55.5 ± 2.2 km s^{-1} on 28-29 December 1990 (Table 1). These observations show also that the radial velocity of this star is not variable. The long time-baseline between the CASPEC and the CORAVEL observations and the constancy of the velocity values are an indication that the star is not part of a binary system.

Table 1 summarizes the above results. The errors on the radial velocities from integrated light, mentioned in this table, are formal errors. A more realistic uncertainty on these values is of the order of ≤ 1 km s^{-1}. For a more detailed discussion about the accuracy of such results, reference is made to Dubath, Meylan and Mayor (ibid. and in preparation).

IV. Stellar Radial Velocities with CORAVEL

The above measurements of radial velocities of individual stars in 47 Tuc are not the first ones done with CORAVEL. During the past decade, a few hundred stars, members of 47 Tuc, have been measured (Mayor et al. 1983, *AA Suppl.* **54,** 495 and in preparation). For a few years, individual radial velocity measurements for a sample of about 50 stars located within the central arcminute (≃ 2 r_c) from the centre of 47 Tuc, have been carried out using CORAVEL mounted on the ESO 1.54-m Danish telescope at La Silla. Most of these stars have several measurements, with a minimum interval of time between two measurements of the same star of about one year.

A histogram of the mean CORAVEL radial velocities is presented in Figure 3. It reveals, in addition to the first high-velocity star (V_r = –55.5 km s^{-1}), a second star (V_r = +13.20 km s^{-1}) with a radial velocity relative to the cluster 3.6 times larger than the velocity dispersion, i.e., V_r(star) – V_r (47Tuc) = +32.4 km s^{-1} with σ_p(core) = 9.1 km s^{-1}. Omitting these two high-velocity stars, this sample of 48 stars gives a systemic radial velocity of –19.2 ± 1.3 km s^{-1} and a dispersion of 9.4 ± 1.0 km s^{-1}.

Values of both systemic radial velocity and velocity dispersion, obtained here from individual radial velocities, are in perfect agreement with those obtained in section 3 from integrated light spectra, i.e., a systemic radial velocity of –18.8 ± 0.6 km s^{-1} and a velocity dispersion of 9.1 ± 1.0 km s^{-1}.

V. Membership of the Two High-Velocity Stars

The first question arising about these two stars concerns their membership. Unfortunately, the relatively low systemic radial velocity of 47 Tuc (V_r ≃ –19 km s^{-1}) does not allow an immediate discrimination between field stars and members of the clusters. A first check consists of looking at their position in the colour-magnitude diagram (CMD). Two CCD images of the core of 47 Tuc, obtained by one of us at the ESO/MPI 2.2-m telescope at La Silla, give a CMD

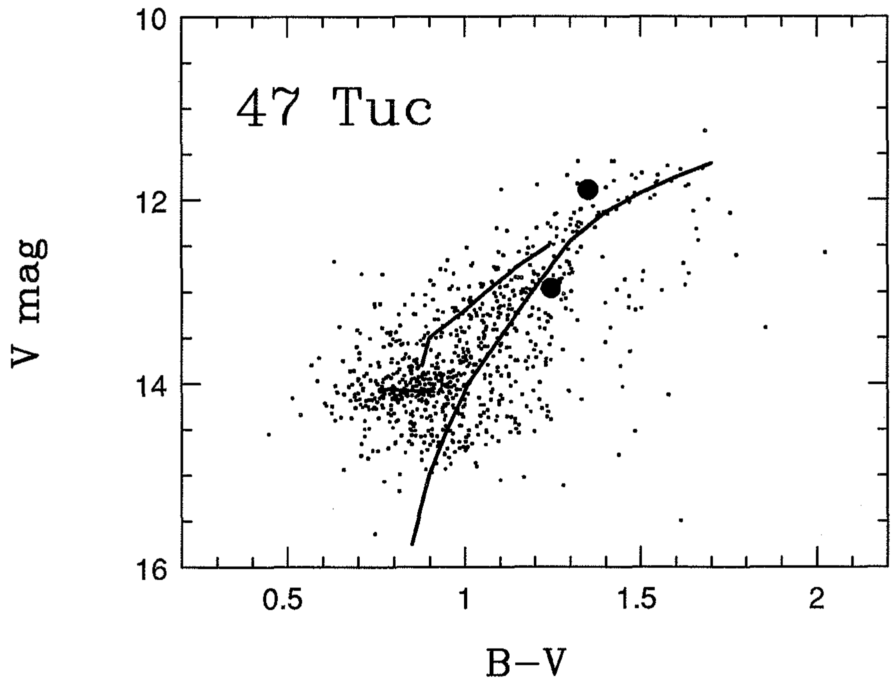

Figure 4: *Colour-magnitude diagram of the centre of 47 Tucanae, from two CCD images obtained at the ESO/MPI 2.2-m telescope at La Silla. The solid lines are the fiducial lines (Hesser et al., 1987,* P.A.S.P. ***99****, 739) for the RGB, HB, and AGB. The two stars (large dots) have positions on the red giant branch and asymptotic giant branch which tend to confirm their membership.*

displayed in Figure 4. The two stars have positions on the red giant branch and asymptotic giant branch which tend to confirm their membership. However, foreground dwarf stars cannot be ruled out since dwarfs at a distance of about 100 pc may appear superposed on the giant branch of 47 Tuc.

Because of its rather high galactic latitude (b = −44°), 47 Tuc does not suffer too strong a galactic pollution by field stars. Ratnatunga and Bahcall (1985) give estimates of the number of field stars per square arcminute toward galactic globular clusters. For 47 Tuc, taking into account a colour range, their estimates give about 1.8 10^{-2} stars per square arcminute. Therefore, the probability to find two such stars inside the central 40″ of 47 Tuc is very low.

From the above considerations there is no reason to disregard these two high-velocity stars; there is no indication that they are not members of the cluster. The ultimate proof of their membership will be obtained if spectroscopy shows that they are giants.

In this context, it is also worth mentioning that Gunn and Griffin (1979, *A.J.* **84,** 752) in their seminal study of the globular cluster M3 (≡ NGC 5272), find two similar high-velocity stars very close to the cluster centre. Their interlopers have velocities at 4.5 and 3.5 sigmas from the mean. In this case, however, the membership of these stars is quasi certain because of the high radial velocity of M3 (about −146 $\mathrm{km\,s^{-1}}$).

VI. Ejected Out of the Core of 47 Tuc?

The main mechanism which may be called upon for explaining these two interlopers is the ejection out of the core by stellar encounters between a single star and a binary, or between two binary stars. Numerical scattering experiments (see, e.g., Leonard, 1991, *A.J.* **1991,** 562) show that gravitational interactions can eject stars at very high velocity. The presence of binaries (the required on-site gunners!) is now confirmed in globular clusters through different kind of observations. Apart from a few binary candidates from variable radial velocity, the core of 47 Tuc contains one low-mass X-ray binary, about ten pulsars and a very high density of centrally clustered blue stragglers recently observed by HST (Paresce et al., ibid.).

Nevertheless, there is a serious shortcoming with the binary interpretation: calculations mentioned above are valid only for ejection of main-sequence stars. So far no study has simulated the ejection of stars with larger radii. Because of their large size, giants cannot be members of close binaries. Their large radii imply larger impact parameters. Therefore, it is not known if the most energetic interactions can involve giant stars, it is not known if such interactions can accelerate giant stars sufficiently to produce such high velocities as observed in 47 Tuc and M3.

Before discussing more accurately the interpretations of these observations and their implications on various possible detailed ejection scenarios, the still tiny but remaining doubt concerning the membership of these high-velocity stars has to be definitely eliminated. The simplest way consists of obtaining spectroscopic observations, and deducing the luminosity classes of the two stars. If they are giants, their apparent magnitudes put them at about the distance of 47 Tuc, where field pollution is absolutely negligible, given the rather high galactic latitude (b = −44°): their membership will be certain. Observing time has been requested in order to get such valuable spectroscopic data. We hope that by the end of the year confirmation of the membership of these two stars will prove that two cannonballs have really been shot out from the core of 47 Tucanae!

STAFF MOVEMENTS

Arrivals

Europe:

ANSORGE, Wolfgang (D), Product Assurance Manager
BEUZIT, Jean-Luc (F), Associate
IWERT, Olaf (D), Electronics Engineer
LATSCH, Hedwig (D), Accounts Clerk
MICHOLD, Uta (D), Librarian
REYES, Vicente (E), Remote Control Operator
URBAN, Ullrich (D), Administrative Assistant, General Services
WIEDEMANN, Günter (D), Infrared Instrumentation Scientist
ZOLVER, Marc (F), Coopérant

Chile:

CORRADI, Romano (I), Coopérant
LUNDQVIST, Göran (S), Associate (SEST)

Departures

Europe:

BERGER, Christian (D), Student
FISCHER, Marianne (D), Administrative Assistant
HALD, Birgit (DK), Administrative Assistant

Chile:

GUNNARSSON, Lars (S), Associate (SEST)