A&A 411, 351–360 (2003)
DOI: 10.1051/0004-6361:20034056

Astronomy & Astrophysics

Long Period Variables in NGC 5128

II. Near-IR properties*

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Received 8 July 2003 / Accepted 1 September 2003

Abstract. Long Period Variable stars are ubiquitous among the bright red giant branch stars in NGC 5128. Mostly they are found to be brighter than the tip of the first ascent giant branch with magnitudes ranging from about $K = 19$ to $K = 21.5$. They have periods between 155 and 1000 days and K-band amplitudes between 0.1 and 2 mag, characteristic of semi-regular and Mira variables. We compare the colors, periods and amplitudes of these variables with those found in old stellar populations like Galactic globular clusters and Galactic bulge as well as with intermediate-age Magellanic Cloud long period variables. The population of stars above the tip of the red giant branch (RGB) amounts to 2176 stars in the outer halo field (Field 1) and 6072 stars in the inner halo field (Field 2). The comparison of the luminosity functions of the Galactic bulge, M 31 bulge and NGC 5128 halo fields shows an excess of bright AGB stars extending to $M_K \simeq -8.65$. The large majority of these sources belong to the asymptotic giant branch (AGB) population in NGC 5128. Subtracting the foreground Galactic stars and probable blends, at least 26% and 70% of AGB stars are variable in Fields 1 and 2, respectively. The average period of NGC 5128 LPVs is 395 days and the average amplitude 0.77 mag. Many more short period Miras are present in Field 2 than in Field 1 indicating a difference in the stellar populations between the two fields. Period and amplitude distributions and near-IR colors of the majority of LPVs in NGC 5128 are similar to the Galactic bulge variables. However, some ∼10% of LPVs have periods longer than 500 days and thus probably more massive, hence younger, progenitor stars. A few carbon star candidates are identified based on their red $J-H$ and $H-K$ colors.

Key words. galaxies: elliptical and lenticular, cD – galaxies: stellar content – stars: fundamental parameters – galaxies: individual: NGC 5128

1. Introduction

In intermediate-age populations (∼1–5 Gyr old) numerous bright asymptotic giant branch (AGB) stars are located above the tip of the RGB. However, bright stars have also been detected above the tip of the RGB among old populations like Galactic globular clusters with [Fe/H] $\lesssim -1.0$ dex and in the Galactic bulge (Frogel & Elias 1988; Guarnieri et al. 1997; Momany et al. 2003), implying the presence of bright AGB stars in metal-rich and old populations. All of the bright giants above the RGB tip in globular clusters seem to be long period variables (LPVs; Frogel & Elias 1988; Frogel & Whitelock 1998). The frequency of LPVs in old metal-rich globular clusters of the MW and in the Bulge has been studied by Frogel & Whitelock (1998). Old populations of lower metallicity are known not to have AGB stars brighter than the RGB tip.

The brightest LPVs in old stellar populations like the Galactic globular clusters and the old disk in the Milky Way reach $M_K = -8$ (Mennessier et al. 2001; Feast et al. 2002; Momany et al. 2003). The higher mass (hence younger) LPVs in the LMC and in the disk of our galaxy can be more luminous, reaching $M_K = -9.4$ (Hughes & Wood 1990; Mennessier et al. 2001).

There exists a long standing debate about the presence of intermediate-age population in dwarf elliptical galaxies and spiral bulges. On the basis of the Wide Field Camera 1 (WFC1) HST data, Holtzman et al. (1993) and Vallenari et al. (1996) concluded that the majority of stars in the Galactic bulge are of

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* Based on observations collected at the European Southern Observatory, Paranal, Chile, within the Observing Programmes 63.N-0229, 65.N-0164, 67.B-0503, 68.B-0129 and 69.B-0292, and at La Silla Observatory, Chile, within the Observing Programme 64.N-0176(B).

intermediate age. Other studies indicated mainly old metal-rich population (e.g. Frogel et al. 1990; Tiede et al. 1995). Newer deep optical and near-IR CMDs suggest that the Bulge is old without even a trace of an intermediate-age population (e.g. Ortolani et al. 1995; Feltzing & Gilmore 2000; Zoccali et al. 2003). In the M 32 dwarf elliptical galaxy the situation might be different, given the presence of an extended giant branch reaching $M_K = -8.7$ ($M_{\rm bol} = -5.5$), indicative of an intermediate-age (∼4 Gyr) population, which has been revealed by near-IR photometry by Elston & Silva (1992) and Freedman (1992). However, it is of interest to note that in the deep optical *VI* photometry of M 32 with HST, no optically bright AGB stars have been found (Grillmair et al. 1996), which might be expected due to large bolometric corrections.

In the gE NGC 5128, Soria et al. (1996), suggested the presence of up to 10% bright AGB stars belonging to an intermediate-age population, based on a *VI* HST CMD. Marleau et al. (2000) made a similar suggestion based on *JH* NICMOS data. Harris et al. (1999, 2000), on the contrary, do not find any bright AGB stars in their *VI* CMDs of two halo fields in NGC 5128. As mentioned above, *V* and *I* bands are not very sensitive indicators of these cool giants and thus some of them might have been confused with first ascent red giants, foreground stars and few stellar blends or stars with larger photometric errors. In the two fields observed in *V* and *K*-bands with VLT (Rejkuba et al. 2001), a large number of bright AGB stars have been detected extending up to bolometric magnitude of −5. Most of these stars have been found to be variables in our long term monitoring programme with ISAAC at VLT. The LPV catalogue has been published by Rejkuba et al. (2003). Here we analyse near-IR properties of these variables and compare them with the LPV population found in the Magellanic Clouds and in the Galactic bulge, with the aim of constraining the contribution of intermediate-age stars to the NGC 5128 halo population.

2. The catalogue

The LPV variables catalogue in NGC 5128 has been compiled and published by Rejkuba et al. (2003). The reader is referred to that paper for the details on the data reduction and the determination of periods. In summary, the observations consist of single-epoch 1-hour exposures in $J_{\rm s}$ and *H*-bands and multi-epoch photometry in $K_{\rm s}$-band obtained with ISAAC near-IR array at ESO Paranal Observatory with UT1 VLT. The two fields observed are located ∼17′ north-east (Field 1) and ∼9′ south (Field 2) from the center of NGC 5128.

$K_{\rm s}$-band observations span a time interval of 1197 days, from April 1999 till July 2002, with 20 epochs in Field 1 and 23 in Field 2. One additional 45 min observation of Field 2 in $K_{\rm s}$-band with SOFI at the NTT at La Silla Observatory brings the total number of epochs to 24 for that field. It should be noted that SOFI near-IR array is a scaled version of ISAAC and that the $K_{\rm s}$-band filters at the two instruments are identical.

The photometry of this homogeneous data set has been performed with DAOPHOT and ALLFRAME software (Stetson 1994). The 50% completeness limits in $K_{\rm s}$ and *H*-bands are at 22.5 for Field 1 and 21.5 for Field 2. In $J_{\rm s}$-band 50% completeness is achieved at $J_{\rm s} = 23.25$ for Field 1 and $J_{\rm s} = 22.5$ for Field 2. To all $K_{\rm s}$-band magnitudes from the catalogue (Rejkuba et al. 2003) we have subtracted 0.1 mag. This was necessary in order to match the observed colors of foreground dwarf and giant stars with that of Bessell & Brett (1988) fiducials (see also Sect. 7.1 and Rejkuba 2003). We have re-checked the photometric calibration and most probably this 0.1 offset in *K*-band is due to an error in the aperture correction. It should be noted that the aperture corrections in such crowded fields are rather uncertain and very difficult to measure accurately.

There are total of 15574 sources in Field 1 and 18098 in Field 2 that were detected in at least 3 $K_{\rm s}$-band epochs. Restricting the detection to $J_{\rm s}$, *H* and 3 $K_{\rm s}$-band epochs the total number of objects is 13 111 and 16 434 in Fields 1 and 2, respectively. Among these there are more than 1500 variable stars. For 1046 red variables, with at least 10 $K_{\rm s}$-band measurements, periods and amplitudes were determined with Fourier analysis and then refined with non-linear fitting of sinusoidal function:

$$K(t) = A\cos\left(2\pi\frac{(t-t_0)}{P}\right) + B\sin\left(2\pi\frac{(t-t_0)}{P}\right) + K_0. \quad (1)$$

In the final catalogue (Rejkuba et al. 2003) periods of variable stars are average values determined from the Fourier analysis and the non-linear sine-curve fitting algorithms, except in the cases where a visual inspection of the light curve clearly preferred one of the two cases. In most cases the two periods were nearly equal (see Rejkuba et al. 2003 for simulations and detailed discussion of period accuracy). Amplitudes, $a = 2\times\sqrt{A^2+B^2}$, and average *K*-band magnitudes are derived from sine-curve fitting.

A close inspection of periods of LPVs lying away from the Mira PL relation indicated a problem of aliasing periods of ∼1/2 and ∼1 year. For a total of 39 variables the most significant period in Fourier periodogram was shorter, approximately 1/2 year, but they could be equally well fit by twice as long periods. These are listed by Rejkuba (2003; Table 1). Other 7 variables have possible shorter periods and for 6 more LPVs improved amplitudes and mean magnitudes have been determined, but their periods remained unchanged to within 3%. In the following analysis periods, amplitudes and mean magnitudes from the LPV catalogue (Rejkuba et al. 2003) will be used except for those listed in Table 1 of Rejkuba (2003). However, the results of our analysis are not influenced by this choice.

3. LPVs in near-IR color-magnitude diagrams

In Fig. 1 we show $K_{\rm s}$ vs. $J_{\rm s} - K_{\rm s}$ color-magnitude diagrams (CMDs) for all the stars detected in at least 3 $K_{\rm s}$-band epochs as well as in $J_{\rm s}$ and *H*-band images that had ALLFRAME photometric errors smaller than 0.25 mag. Field 1 CMD is displayed in the left and Field 2 in the right panel. Long period variable stars with reliably determined periods (significance parameter from Fourier analysis <0.7) are indicated with red circles and green boxes indicate those with less reliable periods (significance ≥0.7). In the following analysis only those variables

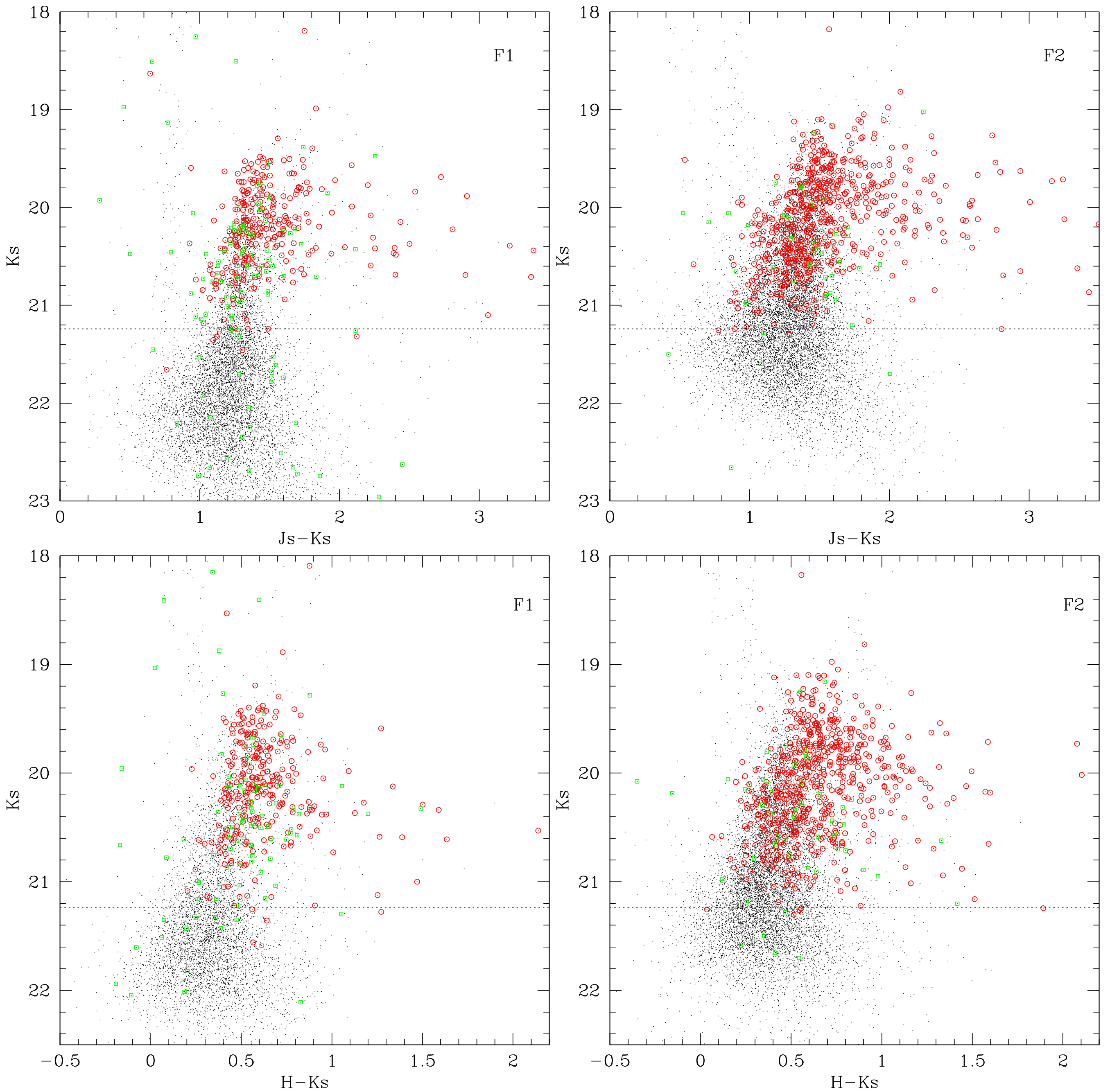

Fig. 1. Top panels: K_s vs. $J_s - K_s$ color-magnitude diagrams for all the stars in Field 1 (left) and Field 2 (right) is shown with black dots. Bottom panels: K_s vs. $H - K_s$ color-magnitude diagrams for Field 1 (left) and Field 2 (right) stars. Variable stars with reliably determined periods (significance parameter from Fourier analysis <0.7) are indicated with red circles and green boxes indicate those with less reliable periods (significance ≥0.7). Dotted line at $K_s = 21.24$ shows RGB tip magnitude.

with better determined periods (significance <0.7) will be used. These are 280 LPVs in Field 1 and 617 LPVs in Field 2.

Dotted line at $K_s = 21.24$ shows RGB tip magnitude measured from the K-band luminosity function (Rejkuba 2003). There is a plume of foreground Galactic stars that are bluer and well separated from the red giants in NGC 5128. According to field simulations from Marigo et al. (2003) they are mainly disk stars. In particular, old disk turn-off stars are expected to be distributed mainly at $(J_s - K_s) \simeq 0.36$, Galactic RGB and red clump stars have colors around $(J_s - K_s) \simeq 0.65$ and low mass dwarfs with $M \leq 0.6\ M_{\odot}$ are found around $(J_s - K_s) \simeq 0.85$. The fact that they are distributed in vertical sequences is entirely due to a range of distances that they span. No Galactic foreground contamination is expected at $(J_s - K_s) \geq 1.0$, where red giants in NGC 5128 are located. The equivalent K_s vs. $H - K_s$ CMDs are shown in the two lower panels of Fig. 1. Here there is some overlap between the regions where foreground sources and red giants in NGC 5128 are located. It should be noted from these CMDs that, due to the much higher density of stars in Field 2 and slightly worse average seeing during the

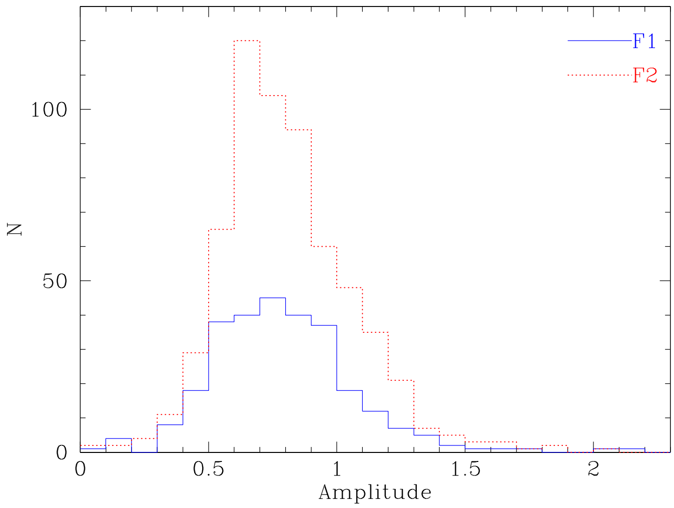

Fig. 2. Histogram showing the amplitude distribution of LPVs in Field 1 (solid line) and 2 (dotted line).

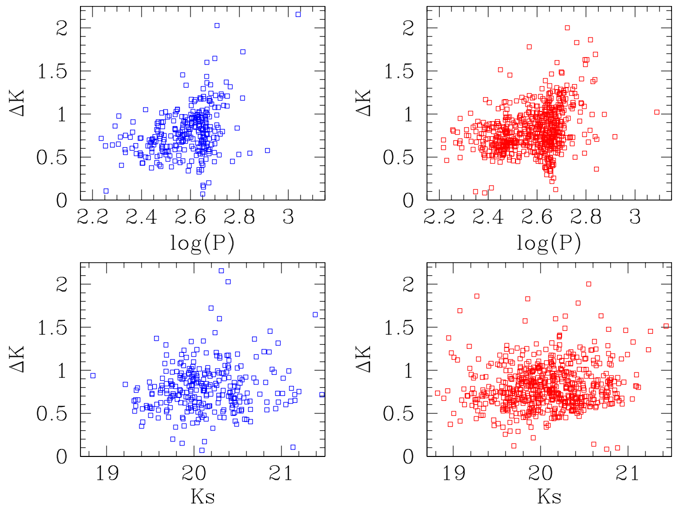

Fig. 3. Amplitudes as a function of periods (top) and mean magnitudes (bottom) for Field 1 (left) and 2 (right).

observations and higher total luminosity sampled, the limiting magnitude is brighter and the photometric scatter is much larger.

The K_s-band magnitude used to compose $J_s - K_s$ and $H - K_s$ colors in Fig. 1 is a single epoch measurement obtained closest in time to the respective J_s or H-band epoch. The time separation between the two is less than 10 days. In contrast, the K_s magnitude plotted on the y-axis is a mean value from all the epochs and it well represents mean magnitudes of AGB stars. If a mean K_s magnitude is used for $J_s - K_s$ and $H - K_s$ color, a much larger scatter in color is observed in the part of the CMD where variable stars are found.

4. Amplitude distribution

Amplitudes of the LPVs in NGC 5128 were determined as peak-to-peak magnitude differences of the best fitting sinusoid light-curve. Figure 2 shows the amplitude distribution of all the LPVs with well determined periods. The majority of variables have K-band amplitudes of around 0.7 mag, with median value of 0.77 in both Fields. The K-band amplitudes for LPVs in LMC (e.g. Wood et al. 1983) and in the Solar neighbourhood (e.g. Whitelock et al. 2000) range between 0.1 and 1.2 mag. Only a few LPVs in the Sgr I field in the Bulge have K-band amplitudes larger than 1 mag with the largest amplitude of 2.5 mag.

The dependence of the amplitudes on the mean magnitudes and on the periods is shown in Fig. 3. As was also found for Galactic Mira-like LPVs (Whitelock et al. 2000), there is a very weak correlation in the sense that longer period variables tend to have larger amplitudes. Similarly Glass et al. (1995) found that the large-amplitude stars have periods longer than 350 days in the Sgr I field in the Galactic bulge.

There are only 32 (out of 897) variables with amplitudes smaller than $\Delta K < 0.4$. Such small amplitude variables usually tend to have fainter magnitudes. Our catalogue is much less complete for these variables. While some of them may have been detected as variable stars, no reliable periods could be measured for them. Semi-regular variables have smaller amplitudes making the detection of periodic variability even more difficult with a small number of observations. Additionally, some of them might not even be detected as variable due to combination of small amplitudes and photometric uncertainty. They might comprise the large majority of the "non-variable" AGB stars detected in Field 1 (see also the next section).

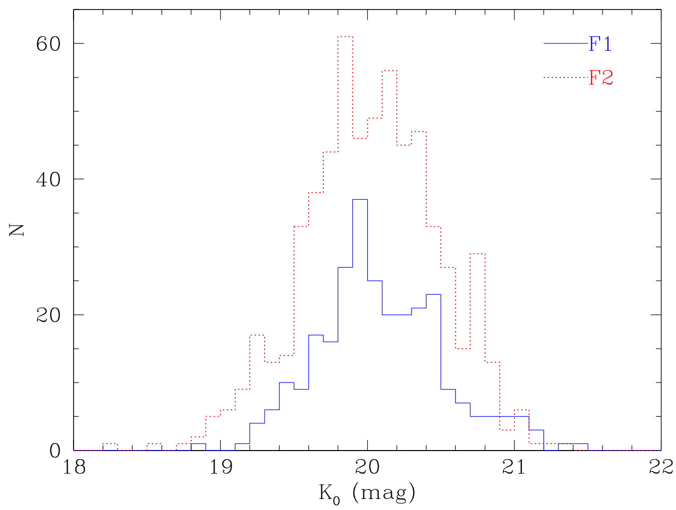

Fig. 4. K-band luminosity function for all variables with well established periods (Fourier analysis significance <0.7) in Field 1 (solid line) and Field 2 (dotted line).

5. Luminosity function

The luminosity functions for all the variables with well determined periods is shown in Fig. 4 with solid line for Field 1 and dotted line for Field 2 LPVs. The luminosity functions in the two fields are very similar.

A detailed calculation of the expected number of LPVs in a ~10 Gyr old stellar population according to Renzini's (1998) work yields 250–500 LPVs in Field 1 and between 350

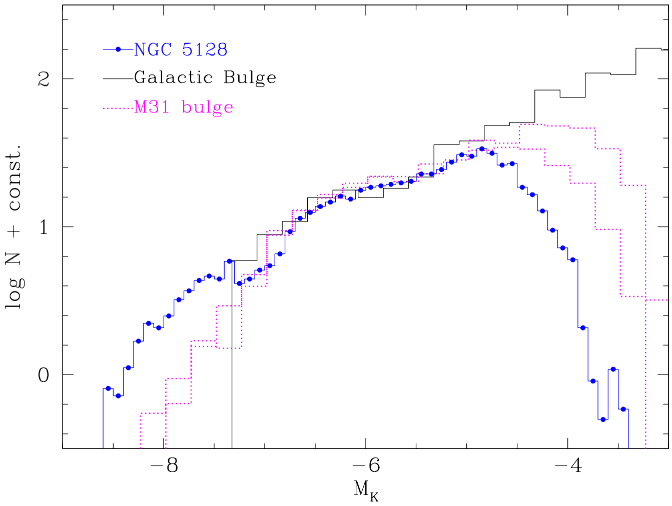

Fig. 5. Comparison of the K-band luminosity functions of Field 1 in NGC 5128 halo (beaded blue histogram) with those of the Galactic bulge (solid black histogram) and of two fields in the bulge of M 31 (dotted magenta histograms). All luminosity functions have been normalized in the range $-6.5 < M_K < -5.5$. The Galactic bulge data are from Zoccali et al. (2003) and the two M 31 bulge luminosity functions are from Stephens et al. (2003; fields F3 and F4).

and 1500 LPVs in Field 2 (Rejkuba 2003). The large uncertainty of the expected number of LPVs in Field 2 comes from highly uncertain total luminosity of this field due to higher number of blends and difficulty to correctly estimate the sky background. The numbers of expected LPVs are in very good agreement with the 437 and 709 LPVs with measured periods in Fields 1 and 2, respectively. This would suggest that the majority of the LPVs belong to an old and metal-rich population similar to that of our Galactic bulge.

Taking into account the foreground Galactic contamination and a probable number of blends, LPVs account for at least 26% and 70% of the extended giant branch population in Fields 1 and 2, respectively (Rejkuba 2003). The completeness of the LPV catalogue in the two fields is rather similar as a function of period and amplitude and thus there seems to be an excess of non-variable bright AGB stars in Field 1. At least some 1150 stars brighter than the RGB tip cannot be accounted for by LPVs, foreground stars or blends in Field 1. In Field 2 this number is an order of magnitude lower and can well be accounted by the incompleteness of the variable star catalogue. Basically all the constant luminosity AGB stars in Field 1 are fainter than $K_s \sim 19.8$. As mentioned above they could be semi-regular variables with amplitudes up to about $\Delta K \lesssim 0.3$ mag, the limit at which the LPV catalogue completeness starts to drop rapidly from ~70%. Virtually no variables with $\Delta K \sim 0.1$ or smaller are expected to be detected according to the completeness simulations (Rejkuba et al. 2003). In Field 2 small amplitude variables could be hidden among blends. It should be noted that in the Galactic bulge and in old and metal-rich globular clusters, no constant luminosity stars are expected to be found above the RGB tip (Frogel & Whitelock 1998; Glass & Schultheis 2002). New, detailed searches for variable stars in the LMC indicate that the large majority of the stars above the RGB tip, as well as many fainter than the RGB tip, are variable (Wood 2000; Ita et al. 2002; Kiss & Bedding 2003).

The positions of the brightest LPVs have been carefully checked on the best seeing images. They show that the three brightest Field 1 variables are much brighter than expected, due to blending. One of them, with $< K > \simeq 18.1$ and $J_s - K_s = 1.75$, is actually blended with a background galaxy and the very blue bright LPV at $J_s - K_s = 0.55$ is contaminated by a bright neighbouring foreground star. The brightest 6 LPVs in Field 2 do not seem to suffer any blending.

The comparison of the Field 1 K-band luminosity function with the luminosity functions of the Galactic bulge (Zoccali et al. 2003) and of two bulge fields of the M 31 (fields F3 and F4 from Stephens et al. 2003) is shown in Fig. 5. All luminosity functions have been normalized in the range $-6.5 < M_K < -5.5$. Taking into account the blends, NGC 5128 Field 2 luminosity function is similar to that of the Field 1 (see also Rejkuba 2003). The tip of the AGB is around $M_K = -7.5$ in the Galactic bulge. However, Mira variables are known in Baade's Window and in Sag I fields that can reach $M_K = -8$ (Glass et al. 1995; Shultheis & Glass 2001), similar to the AGB tip observed in the M 31. In NGC 5128 there are many more AGB stars and the tip of the AGB is more than half a magnitude brighter, clearly implying the presence of the intermediate age population in the halo. The tip of the AGB, measured from the average K_s-band magnitude of the LPVs, is $K_0 = 19.3$. Rejkuba (2003) has measured distance modulus of NGC 5128 of 27.92 ± 0.19 mag, implying that the brightest AGB variables in NGC 5128, which are not brightened by blending, have $M_K = -8.65$. Bolometric corrections were calculated from Montegriffo et al. (1998) and the brightest AGB variables in Field 1 have $M_{\rm bol} = -5.3$, while there are few Miras in Field 2 that reach reach $M_{\rm bol} = -5.7$ mag. The brightest LPV in Field 2 has actually $M_K = -9.78$ and $M_{\rm bol} = -6.43$. Its red colors suggest that it is a long period variable. Its period is 696 days and it lies ~0.8 mag above the Mira PL relation (Rejkuba 2003). Its amplitude is 0.36 mag, rather low for its long period. Unless it is a blend of two perfectly aligned stars (hence not visible on 0.″36 image), it is a good candidate for a hot-bottom burner (Blöcker & Schönberner 1991).

6. Period distribution of LPVs

The distribution of periods for all the variables with good periods is shown in Fig. 6. The distributions for Field 1 and 2 are similar at the long period end, but there is a clearly larger percentage of stars with periods in the range of 250−300 days in Field 2. This is the same period range as the old and metal-rich LPVs in Galactic globular clusters. Since the completeness of the variable star catalogue in this period range is of the order of 80−90%, the larger number of short period variables in Field 2 indicates differences in the stellar populations.

The shortest periods are 160 and 155 days, respectively. The longest reliable periods are 1097 in Field 1 and 1229 in Field 2. Due to the limited time interval spanned by the observations, amounting to 1197 days, most of the variables with well determined periods, hence observed through at least one to two periods, have periods shorter than 600−700 days. If

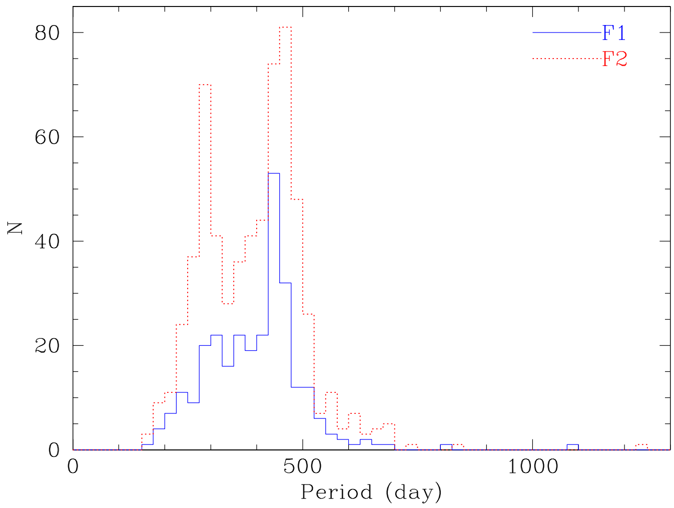

Fig. 6. Histogram showing the period distribution of LPVs in Field 1 (solid line) and 2 (dotted line).

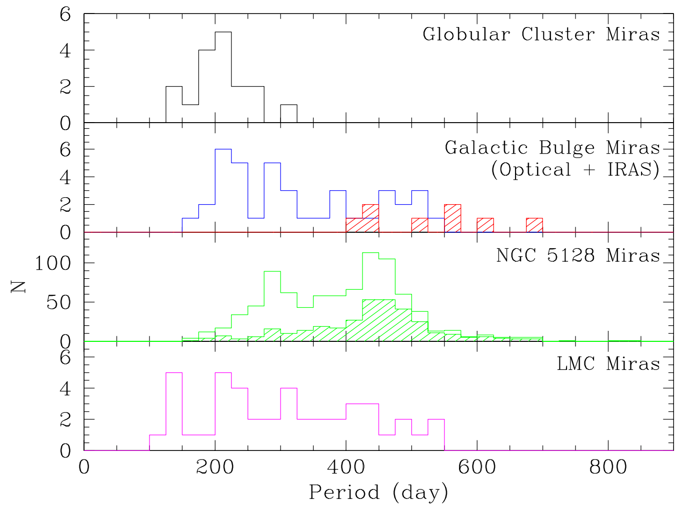

Fig. 7. Comparison of period distributions for Miras in globular clusters (Feast et al. 2002), in the Galactic bulge Sgr I field (Glass et al. 1995) and in the LMC (Cioni et al. 2001) with NGC 5128 Miras in both fields studied in this work. Optically discovered Miras in the Sgr I field in the Galactic bulge are shown as open histogram, while the 10 IRAS sources identified in the same field are plotted with shaded histogram. Miras ($\Delta K > 0.4$) in NGC 5128 with $J_s - K_s$ colors redder than $J_s - K_s > 1.6$ are shown with shaded histogram.

there is a larger population of variables with periods in excess of ∼700 days, only those with larger amplitudes would be detected. The steep drop in the period distribution present already around $P = 500$ days indicates that there is no significant population of such very long period variables. In the present distribution, LPVs with periods longer than 500 days make 10% and 11% of the population in Fields 1 and 2, respectively. For periods longer than 550 days, the contribution to the distribution drops to 4% and 6%. The average period of 897 LPVs with well determined periods is 395 days. For 52 variables, periods were revised by Rejkuba (2003). If instead, for all the stars periods from the LPV catalogue (Rejkuba et al. 2003) are used, the average period is 388 days.

There are 58 variables in Field 1 and 25 in Field 2 for which best fitting periods were shorter than 150 days. However, all of these period determinations are less secure. Some short period variables, belonging to Cepheid class are expected to be found in Field 1 where a conspicuous recent star formation is observed (Mould et al. 2000; Rejkuba et al. 2001). Their colors would be bluer than those of Miras and semi-regulars. Most of the blue variables detected in our fields are unfortunately blended with foreground stars.

The period distribution of LPVs in NGC 5128 can be compared with period distributions of LPVs in other stellar systems (see Fig. 7). In old and metal-rich Galactic globular clusters, Miras span a rather narrow range of periods $140 \lesssim P \lesssim 310$ (Feast et al. 2002), while local Miras have periods ranging from ∼100 to ∼550 days (Whitelock et al. 2000). According to Whitelock et al. (1991) there is no significant population of Miras with periods longer than ∼700 days in the Galactic bulge. However, their result is in disagreement with Harmon & Gilmore (1988) and Blommaert et al. (1998). These last authors found some OH/IR variables with periods in excess of 2000 days in the Galactic bulge. Glass et al. (1995) and Schultheis & Glass (2001) have analysed Sgr I field and Baade's window in the Galactic bulge. The average period of 70 LPVs in Sgr I field is $P_{av} = 333$ day. In the Galactic Centre field the average period of LPVs is 427 days, while that of the OH/IR stars amounts to 524 days (Glass et al. 2001). Apparently, longer-period, hence younger, LPVs are concentrated more towards the Galactic Centre, where a mix of young and old populations is observed due to a recent ($\lesssim$1 Gyr old) starburst.

Glass et al. (1995) discussed the dependence of the type of LPVs discovered on the technique, in the sense that optical searches found principally shorter period Miras, while infrared techniques (IRAS and OH/IR sources) preferentially found longer period Miras. In our near-IR search, most of the short and longer period Miras should be discovered, with the exception of the most dust enshrouded OH/IR sources, if these were present. We find in our fields as well that the periods of the redder Miras are typically longer as shown by the shaded histogram in Fig. 7. Unfortunately due to rather low statistics it is not possible at this moment to make similar comparisons in other systems.

In the LMC LPVs (including Mira and SR variables) span a range of periods from about 20 to ∼1000 days (e.g. Wood 2000; Cioni et al. 2001; Kiss & Bedding 2003).

It has been now quite firmly established that the period of Mira variables represents a good indicator of the stellar population to which it belongs (Feast & Whitelock 1987). Longer period Miras are expected to have higher mass progenitors and therefore belong to a younger population (e.g. Iben & Renzini 1983; Jura & Kleinmann 1992a, 1992b; Kerschbaum & Hron 1992; Feast & Whitelock 2000).

Unfortunately a precise empirical calibration of the initial mass or, equivalently, the age vs. period of Miras is lacking. It can be either inferred from the kinematical properties of Miras

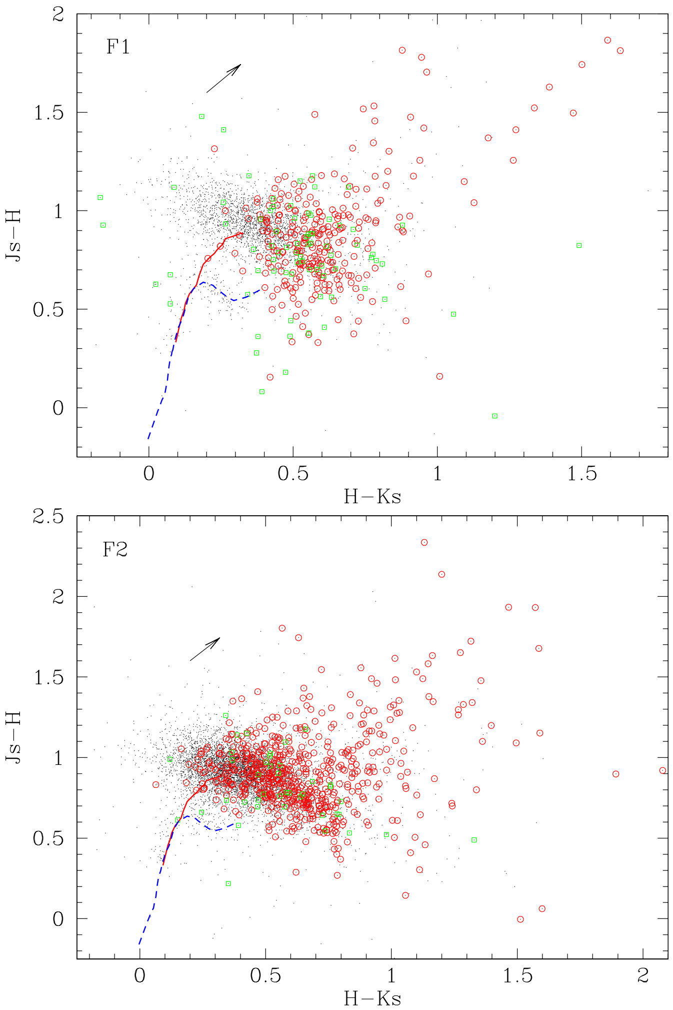

Fig. 8. Color-color diagrams for all the stars with ALLFRAME photometry errors smaller than 0.25. LPVs are indicated with red circles (secure periods) and green squares (less certain periods). Reddening vector for $E(B-V) = 0.5$ is shown. Lines indicate intrinsic colors of Galactic giants (solid red line) and dwarfs (dashed blue line) from Bessell & Brett (1988).

in the solar neighbourhood (Feast 1963; Feast & Whitelock 2000), or from the observations of Miras in simple stellar populations like star clusters. According to Feast & Whitelock (1987), the kinematic age of a 400 day Mira is of the order of ~5 Gyr and an 850 day period Mira would be younger than about 4 Gyr. Feast (1996) on the other hand explored the metallicity dependence of the mass-period relation for Miras and suggested that a 400 day Mira with a solar metallicity would have a mass of ~1.4 $M_{\odot}$. According to models (Iben & Renzini 1983; Vassiliadis & Wood 1993) a 400 day Mira would have initial mass of about ~1.0 $M_{\odot}$. However, it should be remembered that the age of the AGB star with a 1.0 $M_{\odot}$ progenitor will strongly depend on metallicity. The more metal-rich, the older the star, assuming a constant mass. For example, the turn-off age for a $Z = 0.004$ star of 1.0 $M_{\odot}$ is ~4.6 Gyr, while a same mass solar-metallicity turn-off star would be 7.7 Gyr old (Pietrinferni et al. 2003, in preparation). Turn-off age for a solar metallicity star of 1.4 $M_{\odot}$ is less than 3 Gyr.

Miras in the old and metal-rich globular clusters have ages of the order of 10–12 Gyr, with corresponding masses of the order of 0.6–0.7 $M_{\odot}$ and periods around ~250 days. Another empirical point, calibrating the mass-period relation is given by Nishida et al. (2000), who have determined periods of 3 Miras in the LMC star clusters with ages of 1.6 to 2.0 Gyr. All three Miras have similar periods ranging from 491 to 528 days and they follow the Mira PL relations determined from shorter-period stars (Feast et al. 1989).

NGC 5128 has a similar period distribution to Galactic bulge Miras, but there is a tail with some ~10% of the Miras having periods longer than 500 days. Unless this is purely due to age-metallicity-period degeneracy, we conclude that this is an evidence for an intermediate-age AGB component in the NGC 5128 halo.

7. Are there C-stars in NGC 5128?

7.1. Color-color diagram

Color-color diagrams for all the stars with ALLFRAME photometry errors smaller than 0.25 are shown in Fig. 8. Magnitudes have been de-reddened adopting a foreground reddening of $E(B-V) = 0.11$ and a Cardelli et al. (1989) reddening law. A reddening vector corresponding to $E(B-V) = 0.5$ is plotted. As for Fig. 1, single-epoch K-band magnitudes closest in time to J and H-band measurements are used to form colors. The solid (red) line is a Bessell & Brett (1988) fiducial to the Galactic giants and the dashed (blue) line is for dwarfs. Bessell & Brett filters have been transformed to the photometric system of ISAAC (Chris Lidman, private communication).

Carbon stars are typically found among intermediate-age metal-poor populations. Single stars enter the AGB phase as oxygen-rich (O-rich) and they can be converted to carbon-rich (C-rich) after the products of nuclear burning are brought up to the surface during thermal pulses. Due to the lower oxygen abundance of a metal-poor star, fewer C-atoms are needed to convert it into a C-rich star than is the case for a more metal-rich star. The ratio of the number of carbon-rich stars to oxygen-rich stars (C/M ratio) can therefore be used to derive metallicity gradients (Cioni & Habing 2003). Detecting carbon stars in NGC 5128 is important because their presence would be a definite proof of an intermediate-age and metal-poor component. Their origin might belong to a recently accreted metal-poor, LMC-like companion galaxy.

Carbon stars in the LMC have $1.5 < J - K_s < 2.0$. Stars redder than $J - K_s > 2.0$ are obscured and can either be O-rich or C-rich (Cioni et al. 2001). In the $H-K$ vs. $J-H$ color-color diagram, carbon stars are located redwards of $H - K \gtrsim 0.4$ and $J - H \gtrsim 0.8$. However, O-rich LPVs can also be found there. According to Bessell & Brett (1988) there should be no O-rich LPVs redder than $H - K \gtrsim 1.0$ and $J - H \gtrsim 1.4$ (see their Fig. A3). There are 11 stars in Field 1 and 15 in Field 2 with $H-K$ and $J-H$ colors consistent with being carbon stars and all but three of them have periods longer than 450 days and the average period of these stars is 526 days. Their mean amplitude is 1.2 mag. All of them have $J_s - K_s > 2.5$. Very

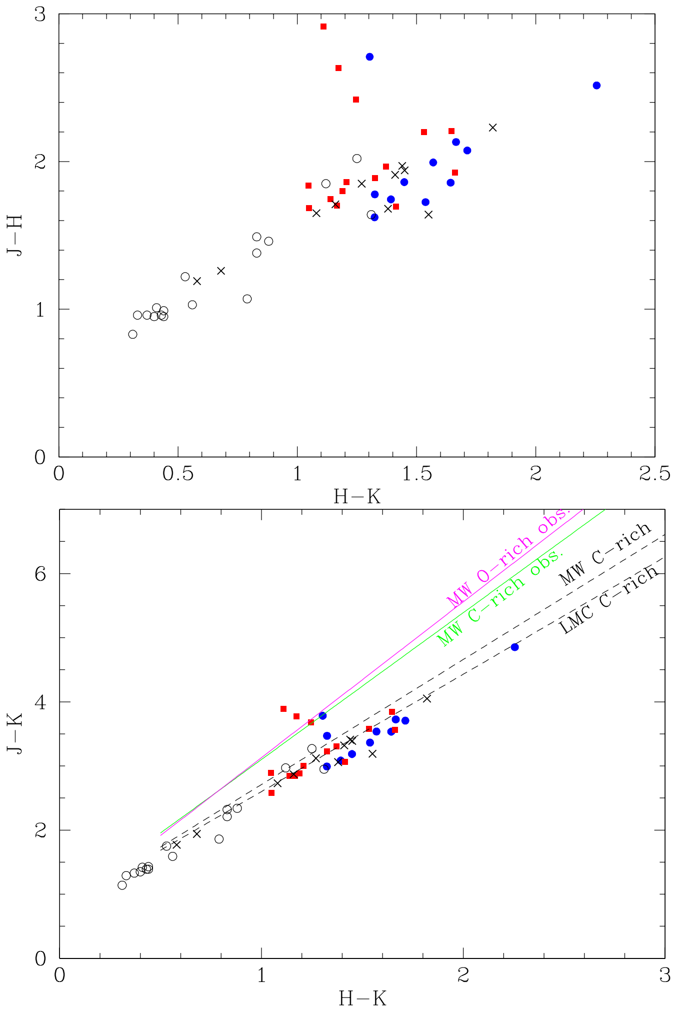

Fig. 9. Bona fide C-star candidates in NGC 5128: LPVs with $H-K \gtrsim 1.0$ and $J-H \gtrsim 1.5$ in NGC 5128 are plotted as filled blue circles (Field 1) and filled red squares (Field 2). Obscured O-rich (open circles) and C-rich (crosses) LPVs in the LMC (Whitelock et al. 2003) are plotted for comparison. See text for the explanation of the model colors.

red $J_s - K_s$ colors and large amplitudes indicate that they probably have circumstellar shells.

A comparison of these stars with obscured C-rich and O-rich AGB variables in the LMC (Whitelock et al. 2003) is shown in Fig. 9. The LMC O-rich AGB stars are plotted with open circles and the C-rich stars with crosses. NGC 5128 candidate C-rich LPVs are plotted as filled blue circles (Field 1) and filled red squares (Field 2). In order to facilitate the comparison, ISAAC data have been transformed into the SAAO photometric system. Cohen et al. (1981) have shown that the $(H-K)$ and $(J-H)$ colors of optically visible C-rich stars in the Milky Way are correlated due to line blanketing by molecular absorption bands (shown as dashed line labelled "MW C-rich"). The correlation for the optically visible C-rich stars in the LMC (dashed line labelled "LMC C-rich") was published by Costa & Frogel (1996), while the correlations for the obscured C-rich (green solid line labelled "MW C-rich") and O-rich (magenta solid line labelled "MW O-rich") Milky Way stars comes from Guglielmo et al. (1993). All four correlation equations are taken from van Loon (1999), who transformed them to $(H-K)$ and $(J-K)$ on the SAAO system. Stars lying along the correlations for obscured O-rich and C-rich stars could belong to either category, but the majority lies along the lines where optically visible C-stars are found. These are bona fide C-star candidates. However, more C-stars could be present among the long-period stars with somewhat bluer colors, but without spectroscopy they cannot be distinguished from the obscured O-rich LPVs.

7.2. Period-color distributions

Color-log period diagrams for NGC 5128 LPVs are shown in Fig. 10. For comparison, a linear fit to the LMC color-log period relations (Feast et al. 1989) are shown as solid lines. They have been shifted to the ISAAC photometric system. It should be noted that these linear relations are valid only for $P < 420$ day. As for Figs. 1 and 8, single-epoch K-band magnitudes closest in time to J and H-band measurements were used to form colors. This produces a large scatter around the mean Period-color relation. The scatter is the largest in $J-H$ vs. $\log(P)$ diagram where the phase difference between the observations is larger and thus some colors might even be non-physical.

$(J-H)_0$ and $(J-K)_0$ colors are likely to be affected differently by metallicity changes, but also by gravity and atmospheric extension. Whitelock et al. (1991) have compared $(J-H)_0$ and $(J-K)_0$ vs. $\log P$ diagrams for the LMC, the Galactic globular clusters, the solar neighbourhood and the Galactic bulge. Their conclusion is that at a given period, colors of Miras in these different environments are very similar. However, Miras in the Sgr I field of the Galactic bulge (Glass et al. 1995) have redder $(H-K)_0$ and slightly bluer $(J-H)_0$ colors than the LMC Miras at a given period, while $(J-K)_0$ colors do not show so large offset. Feast (1996) reports the mean $(J-K)_0$ color-period relation for Sgr I Miras studied by Glass et al. (1995) which has quite a different slope with respect to the LMC relation. He ascribes the difference to metallicity differences. The Sgr I relation is shown in the $(J-K)_0$ color–log P diagram as a long dashed line. It provides much better fit to NGC 5128 LPVs and suggests a similar metallicity as in the Galactic bulge. The large scatter around the color-period relation due to random phase J_s-band observations and possible abundance spread within NGC 5128 halo (e.g. Harris et al. 1999; Rejkuba et al. 2001) prevents us from drawing more quantitative comparison. Some very red stars are present among the longest period variables in NGC 5128. This has also been seen in the LMC, the solar neighbourhood and the Bulge (Glass et al. 1995; Kiss & Bedding 2003), and is ascribed to the presence of cool circumstellar shells arising from mass loss. Such shells contribute principally at longer wavelengths creating an infrared excess. Actually there are 113 sources in Field 1 and 236 in Field 2 with K_s-band magnitudes brighter than the RGB tip and no J_s or H-band counterparts. Many of these could be dust enshrouded LPVs similar to those found in the central parts of the Milky Way by van Loon et al. (2003). Unfortunately, periods could only be measured for a handful of them.

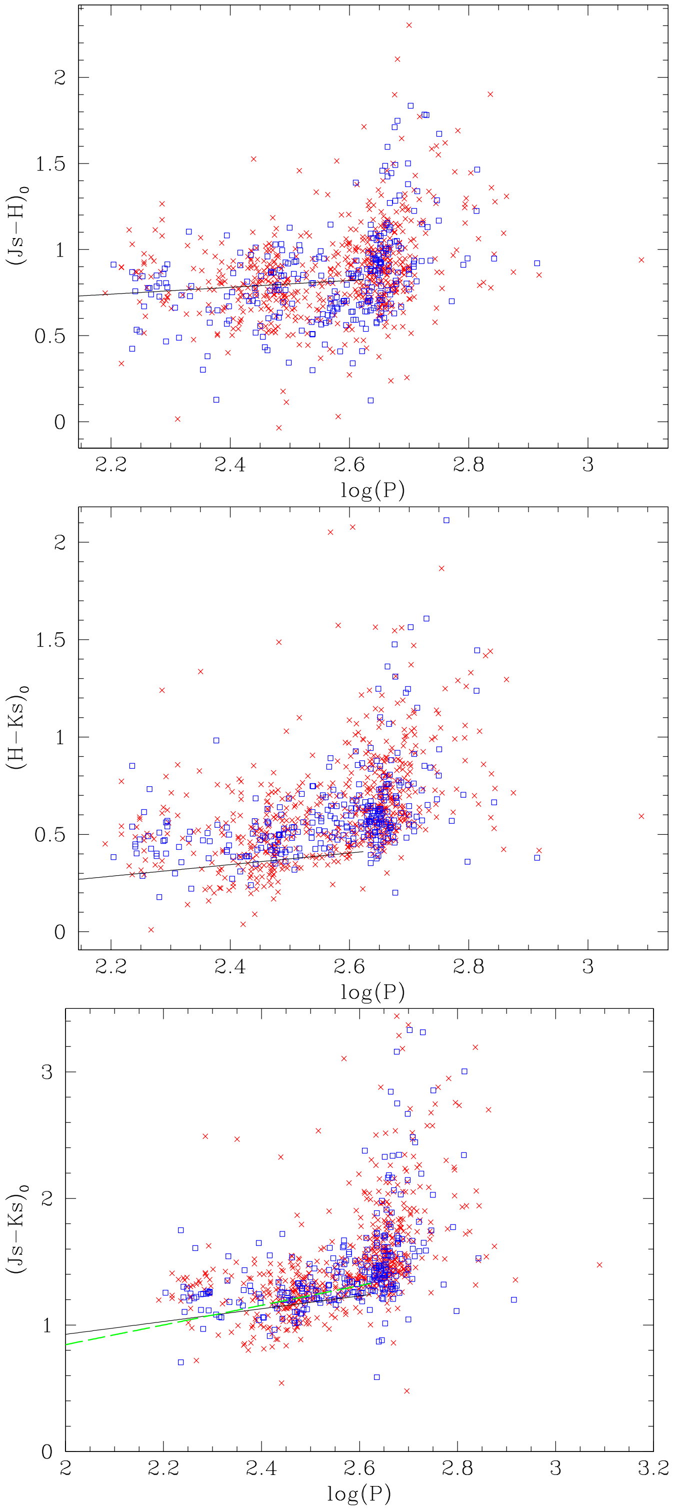

Fig. 10. Period-color relations. For comparison a linear fit to the LMC period-color relations (Feast et al. 1989) is shown (solid line in all three panels). In period-($J - K$) diagram a linear fit to Sgr I Miras (Glass et al. 1995) is shown with dashed line.

8. Conclusions

We have analysed near-IR properties of 897 LPVs with well determined periods and J_sHK_s photometry in two halo fields in NGC 5128. Mostly they are found to be brighter than the tip of the RGB ($K_s < 21.24$; Rejkuba 2003) with magnitudes ranging from about $K = 19$ to $K = 21.5$. They have periods between 155 and 1000 days and K-band amplitudes between 0.1 and 2 mag, characteristic of semi-regular and Mira variables. They obey the same period-luminosity relation as found in the Magellanic Clouds, Solar neighbourhood and the Galactic bulge (Rejkuba 2003). Here we have compared the colors, periods and amplitudes of these variables with those found in old stellar populations like Galactic globular clusters and Galactic bulge as well as with intermediate-age Magellanic Cloud long period variables.

There is an excess of short period, globular cluster-like, Mira variables in Field 2 showing the differences between the stellar populations of the two fields. The brightness of the AGB tip, which occurs around $M_K = -8.65$ in NGC 5128, corresponding to $M_{\rm bol} = -5.3$, compared to $M_K = -8$ in the Galactic bulge (Zoccali et al. 2003) and in the M 31 bulge (Stephens et al. 2003), is an evidence for a ~4 Gyr old component (Mould & Aaronson 1982). Some 10% of the long period $P > 500$ day Miras are expected to have ages younger than 7 Gyr and could be as young as 3–4 Gyr old. Approximately two dozen C-star candidates are identified, but more could be present among the reddened long period variables. C-stars are expected to be found only among metal-poor AGB stars.

Acknowledgements. We thank Chris Lidman for providing the transformation equations for ISAAC filters and Santi Cassissi for providing the stellar evolutionary tracks used to estimate ages. MR thanks M.-R. Cioni and A. Renzini for some interesting discussions. DM is sponsored by FONDAP Center for Astrophysics 15010003. TRB is grateful to the Australian Research Council and P. Universidad Católica for financial support and to the DITAC International Science & Technology Program.

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