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K GIANTS IN 47 TUCANAE: DETECTION OF A NEW CLASS OF VARIABLE STARS[1]

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ABSTRACT

We report the discovery of variability among K giants in the globular cluster 47 Tucanae, using a time series of U exposures with the *Hubble Space Telescope*. The variables lie along a narrow band in the color-magnitude diagram, joining the faint end of the asymptotic giant branch to the red giant branch. The variations, if coherent, mostly have periods between ∼2 and ∼4 days, consistent with low-overtone radial pulsation or nonradial pulsation, and V amplitudes in the range 5–15 mmag, which explains their nondetection so far in clusters. One of the variables may have a period of 1.1 days and a V amplitude of 5.3 mmag. These stars define a new class of variable stars and probably contain variable field K giants such as α Boo as members. An understanding of their variations may have significant ramifications for theories of stellar structure and stellar evolution.

Subject headings: globular clusters: individual (47 Tucanae) — stars: oscillations — stars: variables: other

1. INTRODUCTION

The study of stellar pulsation has significantly advanced several fundamental fields of astrophysics, notably the theories of stellar structure and stellar evolution and cosmological studies of the age and size of the universe. The radial pulsators such as Cepheids and RR Lyrae stars have relatively large amplitudes and have been used both as distance indicators and to constrain stellar models. Nonradial pulsators have smaller amplitudes; however, the greater number of modes provides even stronger constraints on stellar models. This new field of study, asteroseismology, has produced tremendous results on the Sun, rapidly oscillating magnetic A stars, and white dwarfs.

Unfortunately, the only recognized class of pulsating stars on the red side of the Cepheid instability strip is the long-period variables (LPVs: Mira and irregular variables). However, variability is starting to be found in a small number of field K giants with periods ranging from around 1 day to hundreds of days. The long-period variations are probably caused by rotational modulation of surface features, but the shorter period variations are probably caused by pulsations. The best studied example is α Boo (Arcturus). Smith, McMillan, & Merline (1987), Belmonte et al. (1990), and Hatzes & Cochran (1994a) have all reported periodic radial velocity variations in α Boo, with periods ranging between 1.8 and 8.5 days. Among other K giants, Hatzes & Cochran (1994b) found a 0.255 day period in the radial velocity curve of β Oph; a 1.84 day period has been reported in the differential velocities of α Tau (Larson et al. 1996a); and a 1.98 day period has possibly been found in δ Sagittarii (Larson et al. 1996b).

Other searches for short-term variability in K giants have yielded mixed results. Walker et al. (1989) studied five K giants and found radial velocity variations on timescales of less than 1 day in α Boo and β Gem, but not in α Ari, α Tau, and α Hya. Although Hatzes & Cochran (1993) found significant night-to-night changes in the radial velocity of α Boo, similar night-to-night variations were found for α Tau, but none for β Gem. Hatzes & Cochran (1994a) failed to find significant variability above the 10 m s^{-1} level in the K giant π Her during an 8 day observing run. Finally, Horner (1996) failed to find variability in four late-type giants with spectral types between G8 III and K2 III, despite high-quality data.

The classification and interpretation of these K giant variations is obviously impossible because of these conflicting observations and the small, inhomogenous nature of the stars sampled. Clearly, then, K giants are yet to be established as a distinct class of variable stars. Walker et al. (1989) suggested that the stars in their sample may represent a new class of radial velocity variable or that they may represent an extension of the Mira variables or the Cepheids and RR Lyrae stars. However, they also admitted their sample may not be a homogenous group. The null detection of variability in certain K giants is particularly mysterious, and Horner (1996) questions whether there is some property of α Boo, such as its composition or age, that separates it from the four giants he observed.

This Letter provides a partial answer to this question by presenting the first known detection of K giant variability in a globular cluster, 47 Tucanae. This observation of K giant variability in a sample of stars with identical masses, metallicity, and reddening is an important step in classifying these variations and using them to constrain stellar structure and stellar evolution.

2. OBSERVATIONS AND DATA REDUCTIONS

The 47 Tuc time series data and its reduction are described in detail in Gilliland et al. (1995) and Edmonds et al. (1996). To summarize, some 20,000 stars were surveyed in the U-band (F336W) with the *Hubble Space Telescope* (*HST*) in a 66″ × 66″ field centered on the core of 47 Tuc with almost continuous observing over 38.5 hr and 1000 s exposure times (the frequency resolution is 7.2 μHz). The precision of the differential photometry is excellent, with rms values of typically 6–7 mmag, for stars on the horizontal branch (see Edmonds et al. 1996, Fig. 4). The data reduction was complicated by x-y motion of the Planetary Camera (PC) detectors relative to the PC field, consisting of two components: (1) a low-frequency drift of ∼1 pixel in the x-direction and ∼0.1 pixel in the y-direction, and (2) a sinusoidal component caused by the

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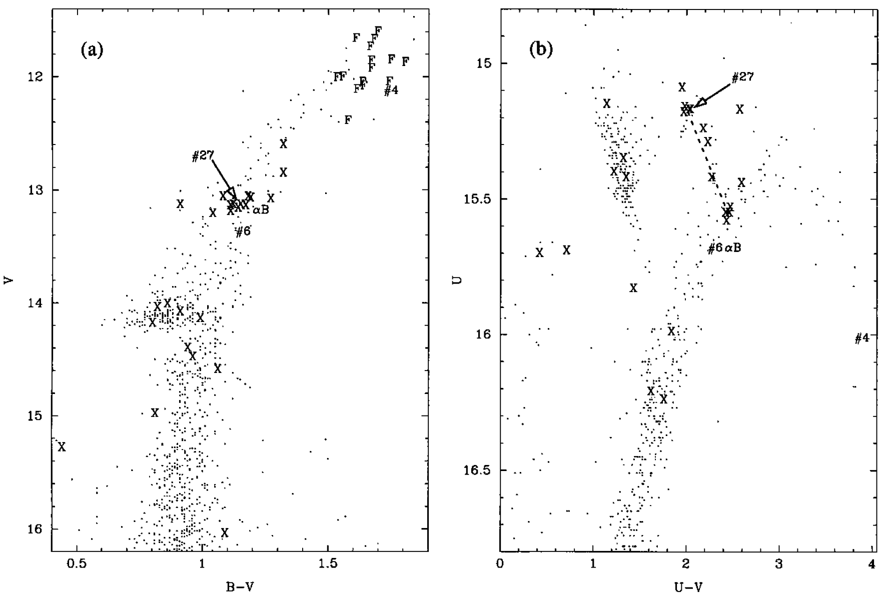

FIG. 1.—The V vs. $B-V$ (a) and U vs. $U-V$ CMDs (b) for stars in 47 Tuc, with crosses for the probable variable stars. Special labels have been used for PV 4, PV 6, PV 27, and the estimated position of α Boo if it were in 47 Tuc. The KGVIS is shown with a dashed line. Superimposed on (a) are the LPVs from Fox (1982).

96 minute orbit of *HST*. Defects in the CCD images and flat fields caused artifacts of this motion to appear in some of the extracted time series.

To search for variables, Lomb-Scargle power spectra (Scargle 1982) of the time series of each star were calculated. We then calculated the false alarm probability (FAP) for each power spectrum, a quantity giving the probability that the peak in a power spectrum would have been produced by Gaussian noise (Scargle 1982). A time series was eliminated from further analysis if the FAP of peaks in its power spectrum near the *HST* orbital period was <0.2 (signifying a likely artifact affected time series, or AATS). A star was considered to be a probable variable (PV) if its power spectrum peak had a FAP $< 1 \times 10^{-6}$ for both the aperture and psf fitting photometry.

3. RESULTS

The variable blue stragglers and main-sequence stars discovered using this search technique have already been discussed in Gilliland et al. (1995) and Edmonds et al. (1996). The subject of this Letter is the surprising number of PVs uncovered on the giant and horizontal branches. Figures 1a and 1b show the V versus $B-V$ and U versus $U-V$ color-magnitude diagrams (CMDs) for the giant branches, where the crosses denote the PVs and the Fs denote the LPVs from Fox (1982). Figure 1a shows that there is a strong clumping of PVs (hereafter called K giant variables or KGVs) near $V = 13.1$ and also a clumping of PVs on or near the horizontal branch (HB). In Figure 1b, the KGVs split into two smaller clumps, one on the asymptotic giant branch (AGB) and one on the red giant branch (RGB), with several other KGVs near a line joining these smaller clumps (hereafter, this line is denoted as the KGV instability strip, or KGVIS).

3.1. *Evidence for Stellar Variation*

The density of the PVs is striking—there are 15 PVs of 76 stars in the range $U = 15$–15.7; $U-V = 1.5$–2.6 (the KGVs), but only four PVs in the range $U = 15 - 15.7$; $U-V < 1.5$, of 210 stars, a factor of 10.4 difference in density of PVs. These two samples of stars have the same range in U and similar values of time series rms and therefore have the same susceptibility to low-frequency artifacts. Thus, even assuming that all four PVs on the HB are artifacts, the density of artifacts on the HB implies that only one or two artifacts should be found in the range $U = 15.0$–15.7; $U-V = 1.5$–2.6. Using statistics, the V and B magnitudes of the PVs in the U range 15–15.7 are distinguishable from the other stars in the same U range at the 99.99% significance level, using the Kolmogorov-Smirnov test.

This clumping in the CMD contrasts strongly with the lack of clumping in position of the PVs—the right ascension and declination of the PVs and their distance from the cluster center are distinguishable from the other stars at only the 80.3%, 77.7%, and 73.4% significance levels (i.e., according to this test, they are indistinguishable). Thus, binaries or stars affected by some exotic form of stellar interaction near the cluster center do not make up a significant portion of the KGVs (the eight eclipsing binaries discussed in Edmonds et al. 1996 *are* obviously centrally concentrated).

To investigate the variability of the KGVs further, Figure 2a shows histograms of normalized rms (rms divided by expected rms normalized to 1) for the aperture photometry for stars in various regions of the CMD *before* removing the AATS. Figure 2b gives a similar plot for the average low-frequency power (in Lomb-Scargle units) between 1.8 and 9.0 μHz. All of the histograms have been normalized to the peak value in the histogram of the KGVs (*solid line*). The secondary peak caused by the KGVs clearly stand out from the other distributions in Figure 2. The rms distributions of the stars on the HB and the KGVs are distinct from each other at the 99.986% confidence level, and the low-frequency power distributions are distinguishable at the 99.991% confidence level. After removing the AATS, the differences between the distributions are maintained.

A sample of aperture photometry time series for the KGVs is shown in Figure 3. Variable 6 is the only time series that may show a full period (period = 1.1 days); however, a sinusoid is

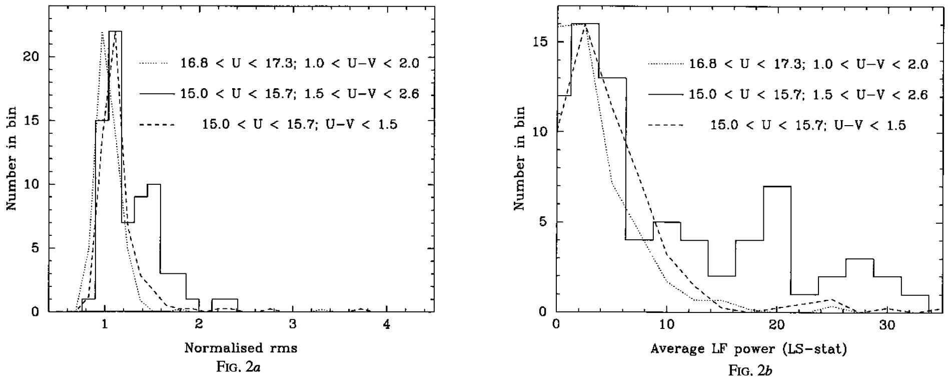

FIG. 2.—Histograms of normalized rms and average low-frequency power for stars in various regions of the CMD

a poor fit to the light curve. Some of the other time series show signs of curvature, such as variable 27, while variable 4 shows simply a straight line trend, as expected for this candidate LPV. For the KGVs (besides variable 6), 13 of the 14 power spectra have one significant peak at the limiting frequency for the data stream length.

3.2. *Periods and Amplitudes*

Simulations and the clumping in the V versus $B - V$ CMD place upper limits on the variability amplitudes. We adopt a simple model of the V magnitude for a single KGV composed of three different terms: (1) a constant, 13.125; (2) a Gaussian noise term representing the rms uncertainty in a single V measurement; and (3) a term chosen with random phase from a sinusoidal light curve (using a large range of periods and amplitudes). Comparing this model with the 12 KGVs having $13.06 < V < 13.21$ gives an upper limit to the KGV amplitude of 38 mmag (in V). This amplitude is not very well determined because (1) the KGVIS may have nonzero width, (2) the rms of the KGVs is only 20% larger than the expected rms for zero amplitude variability, and (3) there are only 12 KGVs used in this calculation.

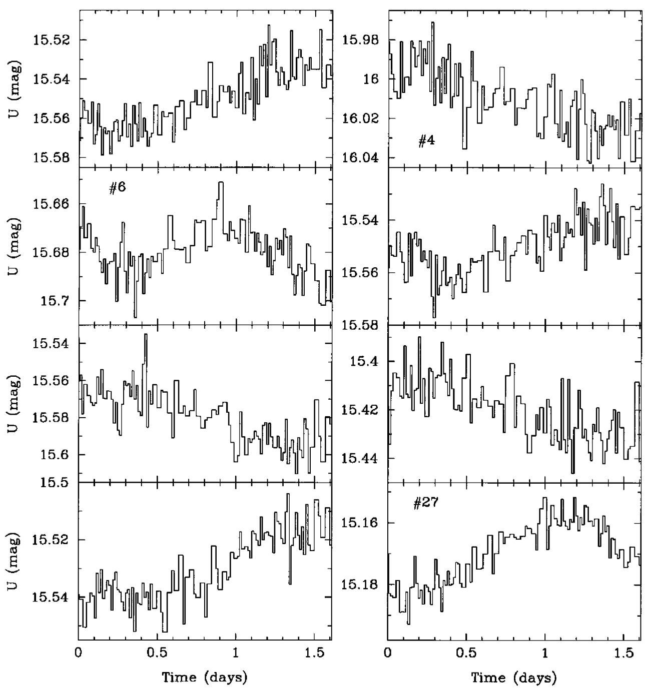

FIG. 3.—Sample time series for the KGVs

To place constraints on the likely periods for the KGVs, realistic power spectrum simulations have been run by adding sinusoids with a range of periods and amplitudes to the time series of stars found on the HB. Even with our relatively short time series, the strong clumping of power spectrum peaks for the KGVs around 5.4 μHz (80%) further constrains the periods of these stars. For test periods of 1.7 days, and in amplitude ranges consistent with the time series, on average 16.2% of the simulations have power spectrum peaks at 5.4 μHz. For simulated periods of 2.2, 2.8, 3.6, 4.6, 6.0, and 7.7 days, the corresponding values are 58.6%, 57.2%, 47.3%, 31.7%, 30.2%, and 24.9%. These figures imply the periods of the KGVs are between ~2 and ~4 days. The lower limit on the period is a strict lower bound, since a large number of time series with periods less than 2 days would easily have been found.

The simulations show that our detection efficiency drops below 50% when U amplitudes fall below ~6–7 mmag for periods between 1 and 2 days (for longer periods, the sensitivity is even poorer). This is consistent with variable 6, with an amplitude of 8.8 mmag having a FAP just below our threshold. Assuming that the average period of the KGVs (apart from variable 6) is 3 days, then their U amplitudes range from 8.8 to 24 mmag, with an average amplitude of (14 ± 4.5) mmag or V amplitudes ranging from 5.3 to 14 mmag, if pulsation causes the variations (see Kjeldsen & Bedding 1995). The histogram of this amplitude distribution rises with decreasing U amplitude, reaching a peak around 12 mmag, before falling rapidly to zero, which suggests the KGV population may extend to much smaller amplitudes.

4. ASTROPHYSICAL INTERPRETATION

The KGVs represent a previously unpublished type of variability in 47 Tuc. As shown by Figure 1*a*, they are fainter and bluer than the LPVs already known in 47 Tuc, which are all AGB members that are brighter than the expected luminosity for core helium flash. Conversely, all of the KGVs are fainter than this limit and lie on both the AGB and the RGB. The periods and amplitudes estimated for the KGVs are also much smaller than those of the known LPVs in 47 Tuc (see, e.g., Fox 1982).

To attempt a simple comparison between the K giants discussed in § 1 and the KGVs, we have used the Bright Star Catalogue (Hoffleit & Jascheck 1982) to estimate U, B, and V for the K giants if they were found in 47 Tuc. If the resulting values are plotted on Figures 1*a* or 1*b*, the scatter is quite large because of mass and reddening differences and uncertainties in distance and magnitude estimates. However, α Boo falls very close to the KGVs, in particular variable 6. Interestingly, the 160 m s^{-1} amplitude measured by Smith et al. (1987) converts into a photometric amplitude at 336 nm of 9.5 mmag, using the work of Kjeldsen & Bedding (1995), very close to the amplitude for variable 6, assuming the period of this variable is 1.1 days.

These results suggest that the variability of α Boo and the KGVs have a common origin. If so, these 47 Tuc observations represent a crucial step in understanding K giant variations, because of the homogenous, relatively large sample of stars. The presence of a new "instability strip" in 47 Tuc might then explain why some K giants vary on short timescales, but others do not (of course, most stars may pulsate at some level—the Sun, for example, is a nonradial pulsator at the μmag level). The physical cause of this instability strip is unknown, particularly because the variations in 47 Tuc are poorly characterized with the short time series. The KGVs could be radial pulsators overstable to an opacity source other than helium, or they could be nonradial pulsators excited by random events such as convection. The KGVs could also be irregular oscillators excited by convection.

Since the period of radial pulsation scales inversely with the square root of stellar density, we can estimate the pulsation period for the KGVs by comparing with known pulsators. Conveniently, the KGVs have temperatures and luminosities lying between those of LPVs and the much shorter period RR Lyrae stars. To estimate the mass and radius of the KGVs, we use the 14 Gyr, [Fe/H] = −0.65 isochrones of Bergbusch & Vandenberg (1992). For $M_V = -0.2$ corresponding to the V magnitude of the KGVs, the isochrones give $B - V = 1.15$, in close agreement with Figure 1*a*. Using the properties of three Mira variables from Frogel (1983) and scaling by density, we estimate the period of the KGVs to be 8–11 days, while using the corresponding figures for six irregular variables from Frogel (1983) gives periods ranging from 4.4 to 9.3 days. These values probably underestimate the fundamental period for the KGVs since the irregular variables and maybe even the Mira variables are probably pulsating in the first or second overtone. Scaling from the periods of type ab RR Lyrae stars (probably fundamental mode pulsators) gives periods for the KGVs of around 5 days. Alternatively, scaling from fundamental periods derived by Hatzes & Cochran (1994a) for two different mass estimates of α Boo gives periods of 4.7 and 5.3 days for the KGVs (variable 6 is fainter than the other KGVs by about 0.2 mag, giving shorter periods of 3.8 and 4.3 days). The reasonably close agreement between these different period determinations suggests that a lower limit to the fundamental period of radial pulsation for the KGVs is 4–5 days. Most of the time series are therefore consistent with radial pulsation, probably in the first or second overtone. However, a 1.1 day period for variable 6 is unlikely to be the result of radial pulsation unless it represents high-overtone modes.

Another possibility is that the variations are caused in part by nonradial oscillations. Applying the equations of Kjeldsen & Bedding (1995) to the KGVs gives a period (P_{max}) of 1.9 days for the nonradial oscillations with maximum amplitude, close to the measured KGV periods. The lower limit to possible nonradial periods is 1.05 days as given by the acoustic cutoff frequency. For variable 6, $P_{max} = 1.4$ days, and the shortest possible period is 0.79 days, and so clearly nonradial oscillations are a good possibility to explain the 1.1 day period. The predicted primary frequency splitting of $\Delta\nu_0 = 1.45$ μHz would be impossible to detect with our data set but may explain the unusual light curve of variable 6.

The amplitude of nonradial modes is estimated, from Kjeldsen & Bedding (1995), to be 1.9 mmag, a factor of 4 smaller than the measured amplitude for variable 6; however, amplitudes are likely to involve the greatest uncertainty in extrapolating from the Sun to red giants. We note that the 14–54 m s^{-1} amplitudes found for α Boo by Hatzes & Cochran (1994a) and the 20 m s^{-1} found for β Oph by Hatzes & Cochran (1994b) correspond to U amplitudes of only 0.8–3.2 mmag, well below our detection levels. This suggests that the KGVIS has nonzero width, with KGV amplitudes strongly peaked at small distances from the middle of the KGVIS and falling off with increasing distance. Further support for this comes from Figure 1*b*, where the low-amplitude variable 6 is located a small but significant distance from the KGVIS.

Obviously, ground-based observations are needed to obtain longer time series on red giants away from the core of 47 Tuc and to characterize variations for these stars. Such observations could, for example, provide a sensitive measure of mass differences between stars on the RGB and those on the AGB. Clearly, much theoretical work is also needed, both to explain the band of variables in the CMD and to predict periods and amplitudes for radial and nonradial pulsations using detailed stellar models. The rewards of such observational and theoretical work, particularly if nonradial modes are present, may have significant ramifications for the fields of stellar structure and stellar evolution.

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