Search for Low–Instability Strip Variables in the Young Open Cluster NGC 2516

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ABSTRACT. In this paper we revise and complete the photometric survey of the instability strip of the southern open cluster NGC 2516 published by Antonello & Mantegazza. No variable stars with amplitudes larger than 0.02 mag were found. However, by means of an accurate analysis based on a new statistical method, two groups of small-amplitude variables have been disentangled: one with periods of less than 0.25 days (probably δ Scuti stars) and one with periods of greater than 0.025 days. The position in the H-R diagram and the apparent timescale may suggest that the stars of the second group belong to a recently discovered new class of variables, named γ Dor variables. They certainly deserve further study. We also present a comparison between the results of the photometric survey and the available pointed ROSAT observations of this cluster.

1. INTRODUCTION

The observation of pulsating variables in homogeneous samples such as stellar clusters is a good way to collect information on the effect of age, chemical composition, and rotation on pulsation.

The studies of open clusters in the northern sky made by several authors (see Slovak 1978) have shown that cluster variable stars of the δ Scuti type, i.e., the typical low–instability strip pulsators, have an incidence of around 30%, apparently independent of age.

The southern open cluster NGC 2516, located at R.A. α(2000) = 7h58m.3 and decl. δ(2000) = −60°52′ is a young cluster believed to have a common origin with α Per, the Pleiades, and IC 2606 (Eggen 1983), but unlike these clusters, it has an unusually high abundance of Ap stars. An extensive study by Mermillod (1981) on young open clusters identifies it as the prototype of a group, named the NGC 2516 cluster group, that also includes NGC 2168, NGC 2301, NGC 3114, NGC 5460, NGC 6025, and NGC 7243. They have almost the same age (log age = 8.3) and are all characterized by a peculiar gap near the turnoff point and by the presence of numerous Ap stars in the extreme blue region of the main sequence.

A first survey for the detection of variable stars in the lower part of the instability strip was carried out by Antonello & Mantegazza (1986; hereafter Paper I) and provided evidence, besides a normal incidence of shorter period variables (P ≤ 0.25 days), of a number of longer period variables (P ≥ 0.25 days), lying on the cool border of the instability strip.

In recent years the presence of variable stars showing small amplitudes with longer timescales than the typical δ Scuti periodicities has been often reported. Mantegazza et al. (1993) first gathered a sample of eight field stars and five cluster stars with very similar locations in the H-R diagram, on or just beyond the cool border of the instability strip, which apparently show a common behavior. They have been named γ Dor stars, and an updated list has been recently published by Krisciunas & Handler (1995).

In the present paper we present previously unpublished observations of NGC 2516 that complete the survey for variability inside the instability strip of the cluster. The survey is complete in the sense that all the stars in the instability strip have been searched for variability.

The absence of a physical lower limit to the possible variability of stars implies the need for a statistical method of data analysis in order to identify the variable stars according to a probability criterion. A method was developed and described in Paper I.

In this paper we present and use a different statistical approach from that used in Paper I, less sensitive to the photometric quality of the night. A comparison between the two approaches is also reported.

2. OBSERVATIONS

A new set of observations was collected at the ESO 1 m reflector from 1987 January 4 to January 9 in the Johnson B filter with the same equipment used in the observations reported in Paper I, i.e., a single-channel photometer with an EMI 6256 photomultiplier. In the first four nights, six stars per night (labeled s₁–s₆) were observed following a cycle s₁–s₂–s₃–s₄–s₅–s₆–s₁–s₂–s₃–s₄–s₅–s₆. The cycle was designed in order to observe in each night and for two consecutive nights two of the stars already discovered as longer period variables (see Paper I), namely stars s₃ and s₅. Five stars were observed in each of the last two nights according to the cycle s₁–s₂–s₃–s₄–s₅–s₆, and in this case no previously known longer period variables were included. Each measurement consisted of 25 integrations.
of 1 s: the number of integrations was increased from that in Paper I in order to reduce scintillation noise. Each observed star was monitored for 7.5 hr, and an average number of 85 and 75 points per star were collected in the last two nights and in the first four nights, respectively.

In order to avoid spurious effects due to variation in air transparency, the analysis was based on differential time series. Since the difference in air mass between the stars observed in each night is very small (<0.005), these spurious effects due to variable air transparencies are significantly reduced.

### 3. Statistical Analysis

In this run, as for the observations reported in Paper I, no comparison stars were assigned a priori: we then do not know which of the stars in each observing cycle are stable or variable. On the other hand, the expected light variations have such small amplitudes (<0.02 mag) that this choice cannot be based on a visual inspection of the differential light curves, so a technique had to be developed that extracts this information from the differential time series between all the possible pairs of stars in the cycle.

In Paper I a statistical approach based on least-squares analysis of differential time series was adopted. For the $n$ stars in each observing night, the variances $s^2_{ij}$ of the $(n-1)$ possible combinations were computed. Under the assumption that each of these variances is the sum of the contributions of the two components

$$s^2_{ij} = s^2_i + s^2_j,$$

the values of such components were estimated by solving the system of $n(n-1)$ equations with $n$ unknowns by means of the least-squares method.

Furthermore, the quantities $s^2_i$ were expressed as $s^2_i = a^2_i + b^2_i + c^2$, where $a^2_i$ is the intrinsic variance of the star brightness, $b^2_i$ is the variance due to the statistical fluctuations of the counts (Poisson’s variance), and $c^2$ is a term that depends on the photometric quality of the night. The $b^2_i$ terms could be estimated through the mean number of counts collected for each star and subtracted, but the $c^2$ term remained undetermined, and statistics could be performed only on the quantities

$$d^2_i = s^2_i - b^2_i = a^2_i + c^2.$$

Variable stars were discriminated on the basis of an $F$-test on the quantities $F_i = d^2_i/I^2_{\text{min}}$.

However, the least-squares–based procedure may not be the best choice. The $n(n-1)$ equations, for instance, are made up of pairs of equations, $(i,j)$ and $(j,i)$, that differ only because in the former the times of the $i$th star have been interpolated to the times of the $j$th star, while in the latter, the situation is reversed. The number of real independent equations is therefore $n(n-1)/2$, which results in poor oversampling with respect to the $n$ unknowns. Furthermore, if the contribution to the variance of the sky and background $c^2$ is appreciable, e.g., of the same order of the intrinsic variances, a least-squares procedure can become unstable.

We therefore decided to make use of a different approach that does not involve the least-squares method. Each differential data point in the series is defined by

$$\Delta m_{ij}(t_k) = -2.5 \log_{10} \frac{I_i(t_k)}{I_j(t_k)},$$

where $I_i(t_k)$ and $I_j(t_k)$ are the counts obtained at the sampling instant $t_k$ and are therefore affected by a statistical error $\sqrt{I_i(t_k)}$ and $\sqrt{I_j(t_k)}$, respectively, due to Poisson’s statistics. Error propagation states that contribution of the statistical error to the variance on the single differential measurement is the following:

$$s^2_{ij}(t_k) = 1.179 \left[ \frac{1}{I_i(t_k)} + \frac{1}{I_j(t_k)} \right],$$

which can be directly subtracted from measured variances

$$s^2_{ij} = \frac{1}{N_{ij}} \left[ \sum_{k=1}^{N_i} (\Delta m_{ij}(t_k) - \Delta m_{ij})^2 \right] - s^2_{ij}(t_k),$$

where $N_{ij}$ stands for the number of measurements in the given time series.

The Poisson-corrected variance may be expressed as

$$s^2_{ij} = s^2_i + s^2_j + s^2,$$

i.e., the sum of the components due to each star fluctuation plus an additional term due to sky and instrumention. Indeed, the term due to sky and instrumentation affects directly the differential measurement and in a first approximation does not depend on the stars observed. Because they have been corrected for statistical noise contribution and sky background, the quantities $s^2_{ij}$ may be considered equivalent to the quantities $a^2_i$ better than those named $s^2_i$ in Paper I: we will therefore refer hereafter to $s^2_{ij}$ as the intrinsic variances.

The information we need to disentangle variables from constant stars, i.e., $s^2_{ij}$, is then distributed into $n-1$ quantities in the form of equation (6) and is contaminated by a systematic background error $s^2_i$.

To extract this information, we compute the summation over each possible differential combination of the $i$th star:

$$S^2_i = \sum_{j \neq i} s^2_{ij} = (n-2)s^2_i + \sum_{j=1}^{n} s^2_j + (n-1)s^2,$$
which is a quantity related to the intrinsic variance $s_i^2$. The term between square brackets is constant for all the stars observed in the night. In order to estimate such a constant term, we summed the quantities (7) over all the stars observed in the night. In order to estimate such a constant term, we summed the quantities (7) over all the stars observed in the night. This gives us a way to estimate the background uncertainty, which is important for understanding the variability of the stars.

By means of equations (7) and (8) we then obtain

$$s_i^2 = \frac{S_i^2}{n-2} - \frac{S^2}{2(n-1)(n-2)} - \frac{1}{2}s_i^2,$$

where the only unknown on the right-hand side is the background term $s_i^2$.

The observational procedure does not allow a precise estimate of the background term $s_i^2$. However, the minimum value among the differential variances obtained in the night under consideration puts an upper limit on this quantity, i.e.,

$$s_i^2 < \min (s_i^2), \quad \text{where } i = 1, n \text{ and } j = 1, n.$$ (10)

Indeed, from equation (6) one can see that $s_i^2$ equals the minimum value if $s_i^2 = s_i^2 = 0$. The minimum differential variances obtained range between 1 and 1.5 $10^{-5}$ mag$^2$.

By introducing this upper limit in equation (8) instead of the real unknown value of background uncertainty, we tend systematically to underestimate the intrinsic variances, the only risk being to assume as constant a variable star. For the purposes of this paper, such a conservative character is welcome.

We then obtained a scale of the background-corrected estimates of the intrinsic variance for each of the stars observed in a given night. As in Paper I we could delineate a limit between constant and variables stars through a statistical $F$-test by comparing the intrinsic variances with the minimum value for the night. However, it should be noticed that the application of an $F$-test here as well as in the context of the analysis of Paper I is not rigorous: indeed, the variances involved are not directly obtained from the original data but rather are derived through some manipulations.

For this reason we preferred to assume a fiducial limit of 2 times the minimum intrinsic variance for the night, i.e., greater than the typical $F$-test value of Paper I.

We report in Table 1 the results of the analysis, while a reanalysis by means of the new procedure of data published in Paper I is reported in Table 2.

A precise estimate of the timescale of variability for the recognized variables cannot be obtained with such a short baseline. Indeed, the average baseline of 0.3 days allows only a poor spectral resolution of 3 day$^{-1}$. However, for the purposes of this paper we are interested only in distinguishing shorter timescale variables ($P < 0.25$ days) and longer timescale variables ($P > 0.25$ days): this information can in fact be extracted even from poor spectral analysis.

We performed a least-squares frequency analysis by means of Vaniček’s (1971) technique and labeled L the stars that...
provided evidence of a reduction factor concentrated at low frequencies ($f < 4 \text{ day}^{-1}$) and S all the other variables (see cols. [3] of Tables 1 and 2).

4. RESULTS

The new set of observations confirmed the variability of seven stars already recognized as variables in the first run, three of them labeled L (C52, C69, and C93) and four of them labeled S (C84, C54, C55, and C51). A further group of three stars (C106, C92, and C64) was pointed out to be variables of type L.

As an example of the quality of the light curves obtained during the survey, differential curves of the shorter period variable C55 and the longer period variable C69 are reported in Figure 1 together with the constant star C97. Each curve is computed with respect to C98, the star showing the minimum intrinsic variance according to the statistics used.

Only a few discrepancies have been found between the results obtained with the old and new approaches in the analysis of the first run and between the results of the two runs. The new analysis of the night HJD 2,446,115 provided the following different results compared with those reported in Paper I: the star C21, indicated as an S variable, was judged constant by the new statistics, while the star C62, previously considered constant, turned out to be an L variable. Such different results are probably due to the imperfect atmospheric conditions on that particular night to which the new statistics are far less sensitive.

The new observations of the stars C96 and C59 do not confirm the variability observed in the first run, while C38, constant in the first run, was classified as S variable in the second run. We notice that all the three stars provided evidence of the highest variance among those observed on the night in which they were classified as variable, so they were very likely varying when observed for the first time.

In the case of C96, this discrepancy could possibly be due to the fact that a longer period variable observed on a short baseline near a maximum or a minimum could easily be misinterpreted as constant. In the case of the short-period variables C59 and C38, one possibility is that we are dealing with multiperiodic pulsators, which is what most $\delta$ Scuti stars are, and the apparent constancy is due to a disruptive beat between different modes. The possible variability of C38 was already discussed by Snowden (1975) and Maitzen & Hensberge (1981).

The four newly discovered L-type variables (C62, C106, C92, and C64), added to the group already pointed out in Paper I (C93, C52, C96, and C69), make up a sample of eight early F-type, longer timescale variables.

5. DISCUSSION

A sample of 44 A- and early F-type stars has been observed in both runs. This sample is complete in the sense that all dwarfs and subgiants with $0.00 < (b - y)_0 < 0.25$ present in the cluster have been observed. Among these stars, six were pointed out to be S variables (13% of the sample, excluding the doubtful cases C59 and C38) and eight to be L variables (18% of the sample). While the incidence of shorter period variables in this cluster, as already stated in Paper I, can be considered normal, the incidence of longer period variables is certainly surprising.

All the stars observed are reported in the H-R diagram shown in Figure 2. The stars are plotted with their absolute visual magnitude $V_0$ versus their dereddened $(b - y)_0$ color index. The Strömgren photometry used as well as the evaluation of the color excess $E(b - y)$ and visual magnitude $M_V$ are published by Snowden (1975); main sequence and borders of the instability strip are taken from Rodríguez et al. (1994).

With the exception of the peculiar case C38, all disentangled shorter period variables fall within the limits of the $\delta$ Scuti instability strip, and they very likely belong to this class of variables. We notice, however, that no $\delta$ Scuti candidate cooler than F0 was found.

Very little can be said about the longer period variables, but it is worth making some speculation on their possible nature. The observed variability is very likely due to intrinsic changes in luminosity of the sources. Indeed, a spurious nature due to an observational effect, e.g., air transparency variations, would unlikely pass the filter of the statistics used: each star is checked against five other selected nearby stars in the cluster. In addition, if the observed variability was due to an observational effect, the stars would have been spread out in the H-R diagram. They are, however, located in a narrow color range.

They could be binaries: there is no way to rule out this...
hypothesis through our survey data. We notice, however, that there is again no reason that in a bias-free sample of stars the binaries should be concentrated on the cold part of the instability strip as they appear to be here.

Could they be intrinsic (pulsating, spotted) variables? Their position in H-R diagram and their apparent timescale suggests they could be γ Dor stars.

The γ Dor stars are variables with timescales in the range 0–5 \( \text{day}^{-1} \) and with typical amplitudes of 0.03–0.1 mag lying in a very narrow region on or just beyond the cool border of the instability strip. Even if some controversy is still present, they have been recognized as the first evidence of nonradial g-mode pulsation among F-type dwarfs. The position in H-R diagram of the most thoroughly studied γ Dor stars is reported (triangles) in Figure 2 for comparison.

Not much of an interpretation can be deduced from survey data of the kind presented in this paper, and the possible γ Dor nature of the longer period variables should be regarded as guesswork.

6. X-RAY DATA

The interaction between pulsation and chromospheric or coronal heating mechanisms has been recently indicated as a possible important tool to collect information both on pulsation mechanisms and heating.

Known single X-ray sources among early F-type stars are generally related with emission from a corona heated by magnetic fields. Two important cases are reported in the literature: 47 Cas (Güdel, Schmitt, & Benz 1995) and 71 Tau (Stern et al. 1994). The former is reported to be a powerful X-ray source showing pseudoregular variability on a timescale of the order of 1 day. Its Strömgren photometry (Olsen 1983) places it in the γ Dor region of the H-R diagram, and the timescale falls in the typical range of the γ Dor optical variability. However, recent photometric observations exclude a light-curve variability of 47 Cas larger than 4 mmag (E. Poretti 1997, private communication). The star 71 Tau is the strongest X-ray emitter in the Hyades; it is a δ Scuti pulsator with spectral type of A9 and large rotational velocity. It is a binary star, but it is difficult to explain the intense X-ray emission as resulting only from the presence of a late-type companion.

The simultaneous availability of our complete survey and ROSAT data on NGC 2516 prompted us to look for relations between variables and X-ray sources.

The open cluster NGC 2516 was observed with the Position Sensitive Proportional Counter (PSPC) at the focus of the X-ray telescope on board ROSAT. This satellite contains an X-ray telescope with a 2° field of view. The PSPC is a gas-filled proportional counter sensitive in the energy band 0.1–2.4 keV, with a spatial resolution of \( \sim 25^{\prime \prime} \) in the center of the focal plane. A detailed description of the satellite and detectors can be found in Trümper (1983) and Pfeffermann et al. (1986).

The observation reported here was obtained on 1992 April 6 with a total effective exposure time of 9284 s. Owing to Earth occultation, radiation belt passages, and observations of other targets, the data were spread over 2 days. The data were analyzed with the XANADU package: first, the event files were taken from the ROSAT on-line archive at the Max-Planck Institute (Munich), and images were extracted. The exposure maps were linearly interpolated and rescaled so as to be overlaid on the images. A boresight correction of \( \sim 10^{\circ} \) was applied. Exposure-corrected count rates or 3 \( \sigma \) upper limits were finally derived (see Table 3).

The analysis showed that none of the suspected variables in the cluster has an X-ray emission (0.1–2.4 keV) above \( \sim 5 \times 10^{30} \text{ergs s}^{-1} \) (assuming a count rate–flux conversion factor of 1 CR = \( 10^{-11} \text{ergs s}^{-1} \text{cm}^{-2} \) and a cluster distance of 440 pc). This upper limit has to be compared with \( \sim 10^{37} \text{ergs s}^{-1} \) for 47 Cas (Güdel et al. 1995) and \( \sim 3 \times 10^{39} \text{ergs s}^{-1} \) for 71 Tau (Stern et al. 1992). It is interesting to note that, despite the nondetection of variable stars, some stars inside the variability strip have been revealed with an X-ray luminosity of a few \( 10^{30} \text{ergs s}^{-1} \).
7. CONCLUSIONS

In this paper we have reported on a survey for variability of a selected sample of A- and early F-type stars in the southern open cluster NGC 2516. The sample is complete in the sense that all dwarfs and subgiants with 0.00 < (b – y) < 0.25 belonging to the cluster have been observed.

The new results confirm the normal incidence of shorter period variables (likely δ Scuti) and the anomalous incidence of longer period variables previously found. The results have been also compared to the survey in the X band obtained by ROSAT, but no relation between variables and X-ray sources could be found.

The statistic used is designed to be less sensitive to spurious effects such as air transparency variations. Observational effects can therefore be excluded, and the variability can be ascribed to variations of the luminosity of the sources.

While the hypothesis of binarity for explaining longer period variables cannot be ruled out through our data, the position they occupy suggests that they may possibly belong to the newly discovered class of γ Dor variables.

If confirmed, the γ Dor nature of the longer period variables in NGC 2516 would be an important result because it is unique among clusters, and the eight objects disentangled in our survey certainly deserve further investigation.

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