WOCS Long-Term Variability in Open Cluster NGC 2141

A. M. Widhalm[1,2]
Physics and Astronomy Department, University of Southern California, Los Angeles, CA 90007
and

S. Kafka
Cerro Tololo Inter-American Observatory
skafka@ctio.noao.edu

ABSTRACT

Old open clusters, located in the disk of the galaxy, are useful tools in understanding the variability of stars in a certain age range. In this paper, we study the old open cluster NGC 2141 which previous to this work has never been studied for variability. Long-term data for this project was taken at the 0.9m telescope at the Kitt Peak National Observatory from November 2004 through December 2005, as a part of the synoptic program. We present initial results of finding variable stars. Of the 100 candidate variables thus far, two have been confirmed to be Algol eclipsing binaries. Future work includes determining variability for the rest of the candidates.

Subject headings: open clusters: general — open clusters: individual(NGC 2141)

1. Introduction

An open star cluster is a group of gravitationally bound stars in the disk of the galaxy which formed from the same molecular cloud. The galactic disk rotates differentially, hence the clusters located towards the center never stay gravitationally bound for more than a few hundred million years. The differential rotation is stronger here, and they collide with much more galactic material, such as large molecular clouds and nebulae. The oldest open clusters are usually found in the outer part of the disk, as they have survived less collisions with large molecular clouds capable of destroying them. As members of the galactic disk, they are metal rich and represent the population of its stars.

Open star clusters are extremely useful because all of their stars have similar ages and chemical compositions. This provides extra information on the stars in the cluster which is more difficult to extract for field objects. In this paper we are interested in searching for and explaining the properties of relatively old (approximately 2 Gyrs) cluster variable stars. Specifically, we hope to find cataclysmic variables (CVs); close-contact binary systems composed of a white dwarf and an M-class main sequence that fills its Roche lobe. These form one of two ways. In one scenario, a star in a binary system becomes a white dwarf (WD) and angular momentum is lost from the system via gravitational radiation until the low main sequence secondary star fills its Roches lobe, in which case accretion onto the WD initiates. In the second, a WD and M-star encounter each other due to a third kinematically active party, the M-dwarf fills its Roche lobe, and then the white dwarf starts accreting mass from the M-star to itself. Neither of these scenarios can happen until one star becomes a WD, therefore, in order to find

[1]Visiting Student Astronomer, REU Program, Cerro Tololo Inter-American Observatory. CTIO is operated by AURA, Inc. under contract to the National Science Foundation.

[2]new address: Astronomy Department, New Mexico State University, Las Cruces, NM

them in clusters, we need to set a lower limit on the age of our cluster. We can approximate this age with the time it takes for an 4 $M_\odot$ star to exhaust its fuel and leave the main sequence. We use a 4 $M_\odot$ star as this is the upper mass limit for a star to evolve into a white dwarf. The stellar lifetime takes around 1 Gyr, plus a couple hundred million years for it to evolve into a white dwarf. Thus we can set a lower limit of on the age of a cluster containing white dwarfs at around 1 Gyr. NGC 2141, at an age of $\sim$ 2.5Gyr, fits the bill perfectly.

NGC 2141, is a prime candidate for our survey as it has not been studied much in this respect. Carraro et al (2001) cite it to be of late-intermediate age at 2.5 Gy and a distance of 4.4 kpc from the sun. NGC 2141 is considered to be relatively metal poor, and its current range in metal abundances, found by Janes (1979) and Geisler (1987) is [Fe/H] = -0.54 $\pm$ 0.42 to [Fe/H] = -0.63 $\pm$ 0.15, respectively. One of the first studies of the cluster, by Burkhead et al (1972), found a differential reddening of E(B-V) = 0.30, but currently this is debated, as Carraro et al (2001) found no differential reddening for this cluster. Friel (1989) found its radial velocity to be $< V_r >$ = 43 $\pm$ 6 km/s.

This cluster has not previously been studied for variability. Hence, we expect to find variable stars in all timescales. An open cluster is effectively a "kitchen sink" of stars; the ingredients are all there to create a plethora of stellar variability according to individual characteristics.

One such example of stars are the Mira variables (Sterken & Jaschek 1996). These stars are long-period pulsating red giants with periods between 80 and 1000 days (Sterken & Jaschek 1996). Mira variables represent a short transition phase on the H-R diagram in the giant branch when a red giant becomes a planetary nebula. The periods of Miras are significant, as they delineate to which population the subject star belongs, implying its chemical composition. Miras with periods of around 200 days are known to have the same chemical abundances of metal-rich globular clusters. A longer period of the pulsation requires the star to be more massive, and this also suggests it is even more metal-rich. Our study is looking in the metal-rich disk of the galaxy, hence longer-period Miras would be more likely found than shorter-periods, as in the globular-cluster class. We have data for almost 400 days, and thus as of yet cannot search for the longest-period, 1000 day, candidates of Miras.

As a function of data available, shorter period variables are much more likely to be found. Eclipsing binaries, such as Algols, are a representative example of such variables. The light curve for Algol binaries consists of two dips, corresponding to the eclipse of the major and minor star, with little to no variability between eclipses. Algol periods can also vary over time or be monotonic, and range from less than a day to nearly 27 years. Those with shorter periods only will be considered here. The constraints that an eclipsing binary be Algol-type include that both stars must be on the main sequence with a spectral type from O to M. If not this case, the candidacy for Algol-type can mean that (1) neither star has filled it Roche lobe, (2) one star overfills its Roche lobe and transfers mass to an under-developed secondary star, (3) the secondary star is still on the main sequence, while the primary is completely evolved to the stage of white dwarf, and (4) neither are evolved (Sterken & Jaschek 1996).

W UMa type variables are eclipsing binaries similar to Algol-type, yet their light curve continues to change between eclipses because the two stars are tidally interactive. Unlike Algol-type binaries, the depth of the eclipses on the light curve is equal, suggesting that they share the same surface temperature. This is possible due to the fact that the two stars have filled Roche lobes, are in contact, and the more massive star transfers luminosity to the other through a common envelope. W UMas consist of a G spectral type and an M type star, and all have short periods, ranging from 0.8 to 1.5 days (Sterken & Jaschek 1996). They are known to populate open clusters and are thought to evolve into cataclysmic variables (CVs), or FK Comae type variables.

FK Comae stars are rapidly rotating variables which can be single or binaries (Sterken & Jaschek 1996). If no companion is published with a candidate star, it is because the primary is too huge and rotating too fast to see the secondary; the single stars in this category are not 100% verified as such. The variability from these spawns from their uneven surface brightnesses. FK Comae result from a W UMa binary system that evolved off the main sequence and then began a merging process. Thus not all have joined to form a single star. Regardless of the type of stars in this class, all have many starspots. In the binary system case this causes a large light variation, while for single giant stars this allows for a variation on the order of only 0.04 m (Sterken & Jaschek 1996). Conversely, single-star FK Comae tend to vary on the order of 20 days while those in binary systems have periods of about 5 days.

Since little is currently known about NGC 2141, we will find luminosity changes in stars for all time scales. In order to encompass as many types of variable candidates as possible, not only CVs, it is necessary for this project to take data as often as possible and for as long as possible.

2. Observations

All observations were taken at the WIYN 0.9 meter telescope at Kitt Peak National Observatory. The S2KB CCD was used, which has a field of view of 20' × 20'. Several different observers contributed to the synoptic survey, taking data under different kinds of photometric conditions. We only used an R filter as it is the most sensitive, and allows us to observe fainter stars. The time period of the observations spans from November 2004 to December 2005. We have data with both long and short exposures, but will only address the long exposures in this paper. The short exposures (90 seconds) only allow the telescope to gather enough light to see the brightest sources. The longer exposures (300s and 600s) allow us to look deeper into the open cluster to find fainter sources. White dwarfs, one component in CVs, are faint stars, hence we need longer exposures to see them. Exposures of 300s were taken in late 2005 in lieu of 600s due to problems with telescope guiding.

3. Data Processing and Reduction

All of the images were bias-corrected and flat-fielded using IRAF. This is a synoptic survey, thus the observer is never the same. As a result, the data taken, including biases and flat fields, are not completely consistent. In several nights there were no biases, no flat fields, or neither. To correct the images from the nights with no biases, we only did an overscan bias subtraction in IRAF. For the

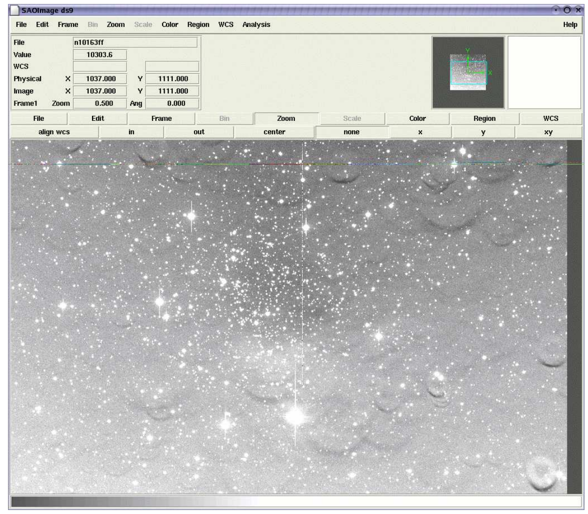

Fig. 1.— This is an example of an image that was not flat fielded properly; no flats were taken for this night. There is a poor CCD column in the center of the image, characteristic of every image taken.

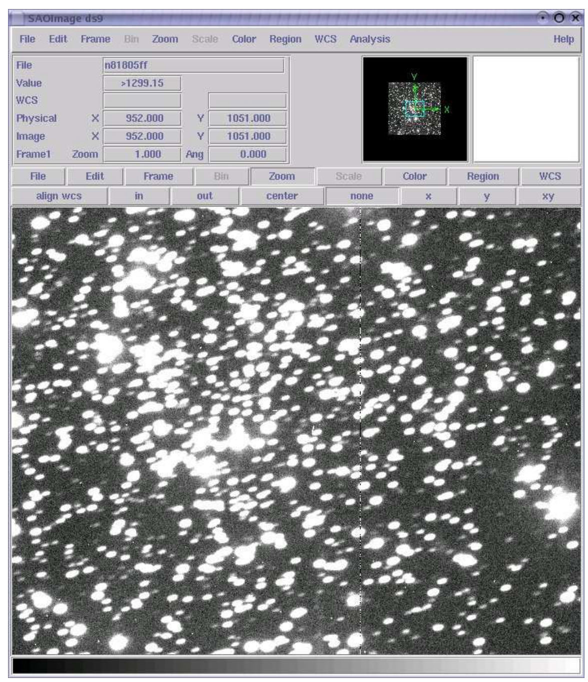

Fig. 2.— The 0.9m telescope at KPNO lost guiding several nights. Data from some nights were saved by taking 300s exposures in place of 600s.

images that did not have corresponding flat fields taken for the same nights, we used the flat fields from a previous night. In most situations, however, this did not correct the image well enough, and thus we had to remove data from nights from our list. An example of a poor image is shown in Figure 1. This is after it has been flat-fielded and bias-corrected, yet there are still "arcs" plainly visible interfering with the scientific content. This problem with flat fields, as seen in Figure 1, corrupted only a few nights; most of the images we threw out were unusable because of poor guiding. Figure 2 shows an example of an image where the telescope lost guiding. It is difficult to do point-source photometry on an object that is not a point, hence these were not used. After filtering out poor images such as this, we were left with approximately 215 epochs of observation for NGC 2141, spanning a period of 85 nights.

After data processing, we had approximately 500 good images from November 2004 to December 2005. Of this, 260 were long-exposure (300s to 600s) data.

We used the DAOPHOT routine in IRAF to do PSF fitting. There are five tasks we ran in DAOPHOT to obtain a final PSF fit. Our step by step tasks are the following:

(1) DAOFIND was used to find the stars in the field.

(2) PHOT found the initial instrumental magnitudes of the stars via aperture photometry.

(3) PSTSELECT selected candidate stars to use to determine a representative psf function for all the stars in the field. This allows the task to choose candidates automatically, which we manually checked in the next step.

(4) PSF ran through 70 stars, prompting us to either accept or reject them for fitting. The criterion for selection was a good point-source star with no neighbors or defects in a surrounding field of two times the full width half maximum. There is a lot of crowding in the center of the cluster, hence most of the PSF stars used were on the outskirts. Figure 2 shows an example of a good PSF candidate star, while Figure 3 shows a poor one. In order to get a good cross-section of a likely fit for stars in the field, we selected at least 40 stars in each image for photometry.

(5) ALLSTAR was then used, applying the PSF function to the rest of the stars to compute the final, PSF-based instrumental magnitude and photometry on each image.

After doing photometry on all of the images with DAOPHOT, we compiled each output file into a larger photometry file and split the field into 9 frames to facilitate the stellar variability search. In the process of this frame splitting, the coordinates of the stars in each epoch were redefined. Following this, we realigned the frames by matching patterns in the stars with reference to the first epoch. Once the frames were aligned, we checked for variability in each starting with the center, more crowded, frame. We used a custom interactive program called AstroVar, written by K. Honeycutt (1992). AstroVar is based on the method of incomplete ensemble photometry. NGC 2141 is only visible to the observer from October to April, thus there is a large gap in the data for the northern summer months. Additionally, much of the data is inhomogeneous during the active observing semester due to inconsistencies with data taking.

AstroVar is a multi-faceted interactive program to help the user identify candidate variable stars. It has five "pages," or windows, of information to aid analysis. I used the first page to identify variable stars, and the second to delete data that was obviously corrupted. This was made plainly visible with a graph the second page projecting instrumental magnitude and seeing conditions. Outliers to the norm were deleted. The first page of this program has three windows to facilitate the search for variable stars. The top left frame, as seen in Figure 3, shows a plot of the deviation of the mean magnitude versus the instrumental magnitude. The objects highlighted in purple deviate from the norm variability for the cluster, i.e. these are the possible variable stars. Not all of these will be true variable stars, however. False variables are caused by photometry errors, which could be a result of cosmic rays, blocked columns, or even false binaries. The latter can be described better as a single star in the front and a single star in the back of the cluster as viewed from us. If on the line of sight to the cluster they appear very close to each other, almost overlapping or blending, they can seem to be variable to due large photometric errors. This proposed star will appear to demonstrate variable properties as a result of different photometric conditions.

The second frame, located in the top right corner of figure 3, shows a finding chart of the cluster plotted in X versus Y for simplicity. In the finding chart we can visually check for false variables caused by either false binaries or close companions, such as a bright star infecting the photometry of a neighboring star. On the bottom of figure 3 is the light curve frame. This is plotted in instrumental magnitude versus Julian date (JD). If we see suspect variability, such as the example in figure 3, we can zoom in to a portion of the light curve to verify its candidacy. This particular star looks as if it displays short-term variability, so it will advance to the next step to determine if it is indeed variable, and if so, what type of variable star it is.

The first step after identifying a possible candidate is to examine if it is a periodic variable, which is done in a custom program called periodogram. This program, as shown in figure 4, displays the same instrumental magnitude versus JD graph as in AstroVar (top) and performs a Fourier analysis to determine a period for the candidate star (Horne & Baliunas 1986). Periodogram suggests this period for the variable to fold into a phase in the next step. We take this kind suggestion, and apply it to a phasing program called lc phase. If the period is obviously incorrect, the magnitude versus phase diagram will not display any periodic variations. In this situation, we iterate between periodogram and lc phase until we settle on a good period, yielding a nice phase, such as in figure 5.

Lc phase plots instrumental magnitude versus phase for the candidate variable star. For our example star, periodogram initially suggested a period of 0.35533 days, and while periodicity was plainly evident, the phase was not accurate enough. I manipulated the period until reaching at a better one of 0.355425 days. The phase for this star with this period is displayed in figure 5. Clearly this object shows periodicity; it is an eclipsing Algol binary system. Algols are easily distinguished with a phase diagram alone. The light curve displays one or two sharp dips when one star is eclipsing the other, depending on the inclination angle of the binary system and the relative sizes of the stars. The most characteristic aspect of Algol light curves is the fact that they show minimal to no variability between eclipses

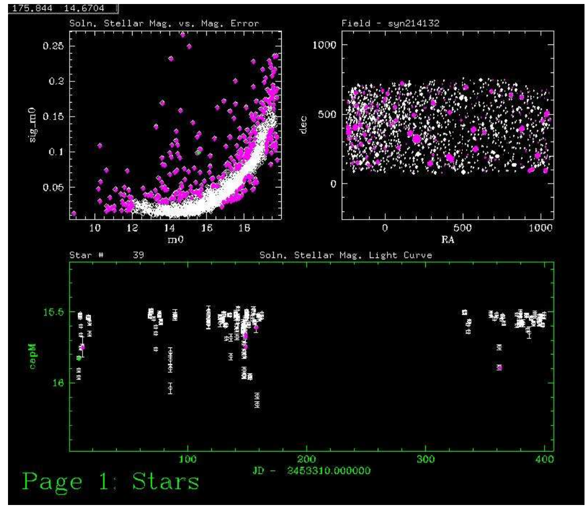

Fig. 3.— AstroVar is a custom interactive program based on the method of incomplete ensemble photometry (Honeycutt 1992).

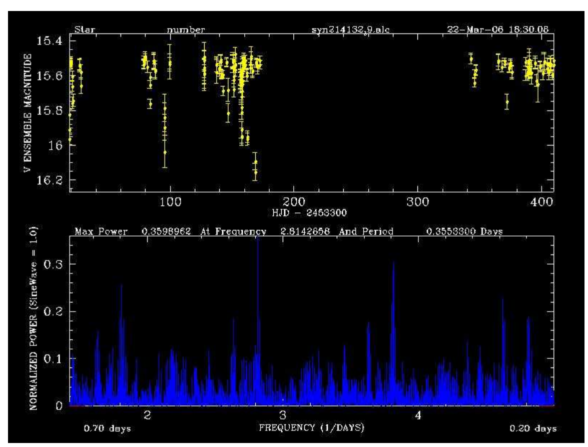

Fig. 4.— Periodogram suggests a period for the candidate variable star.

(Sterken & Jaschek 1996). A model example is displayed in figure 5.

4. Results

The first round of results indicates that NGC 2141 contains variable stars. We have identified thus far two Algol binaries, shown in figures 5 and 6. Nevertheless, there is still much to do in the future.

5. Conclusions and Future Work

Previous to this work, NGC 2141 had not been studied for stellar variability. We used photometric data from the WIYN 0.9m telescope over three observing semesters to ascertain its variability. Several of our candidate variables display long term periodic dependence, and will be examined for true periodicity in the near future. Two of our stars were discovered to be short period Algol eclipsing binaries.

At this time in our study, we have a preliminary list of 100 variable stars. They need to be checked in AstroVar to determine if are true or false variable stars.

Using WOCS data, we plan to check the photometry of NGC 2141 in the B and V filters to determine the positions of the variables on a V versus B−V color magnitude diagram. This will give us more information about the type of variables we may find in this cluster.

Finally, we will resolve whether the variable stares we find are members of this cluster. This will be facilitated by looking at the position of the star in the cluster plus its position on the color-magnitude diagram.

The research in this paper was made possible by the REU program sponsored by the National Science Foundation. Special thanks goes to Cerro-Tololo Inter-American Observatory for hosting the 10-week program. The author would like to personally thank Dr. Styliani Kafka for extensive guidance and patience, and for being a fantastic REU director.

Facilities: CTIO.

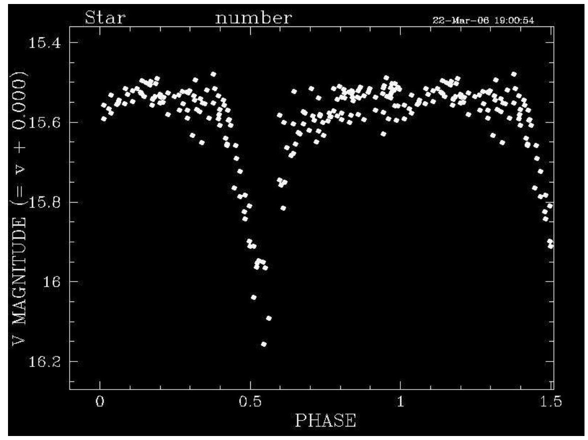

Fig. 5.— This is the same star as in figure 4. It has been positively confirmed as variable. From the light curve shown above, we can see that it is an Algol eclipsing binary.

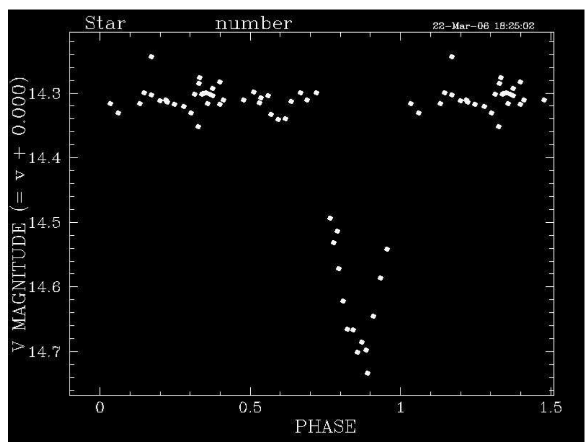

Fig. 6.— The second Algol binary found is shown above. It does not have as many data points as the variable star in figure 5, yet displays a characteristic Algol light curve.

REFERENCES

Burkhead, M. S., Burgess, R. D., & Haisch, B. M. 1972, AJ, 77, 661B

Carraro, G., Hassan, S. M., Ortolani, S., & Vallenari, A. 2001, A&A, 372, 879-884

Friel, E. D. 1989, PASP, 101, 244-249

Geisler, D. 1987, AJ, 94, 84

Geisler, D. 1984, AJ, 287, L85-L89

Horne, J., & Baliunas, S. 1986, ApJ, 302, 757-763

Honeycutt, K. 1992 PASP, 104, 435-440

Janes, K. A. 1979, ApJ, 39, 135

Rosvick, J. M. 1995, MNRAS, 277, 1379-1384

Sterken, C., & Jaschek, C. 1996, Light Curves of Variable Stars, a Pictorial Atlas, Cambridge University Press

This 2-column preprint was prepared with the AAS LaTeX macros v5.2.