A LARGE-SCALE SURVEY FOR VARIABLE STARS IN M 33

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Abstract. We have started a survey of M 33 in order to find variable stars and Cepheids in particular. We have obtained more than 30 epochs of $g'r'i'$ data with the CFHT and the one-square-degree camera MegaCam. We present first results from this survey, including the search for variable objects and a basic characterization of the various groups of variable stars.

1 Introduction

The effect of metallicity on the luminosity of Cepheids (and its subsequent impact on the distance scale) is not well known. A number of efforts in the last decade have shown that this effect is not very large (e.g. Sasselov et al. 1997; Kochanek 1997; Kennicutt et al. 1998; Sakai et al. 2004, Macri et al. 2006). It can, however, have a significant impact on the value of the Hubble constant when it is measured via Cepheids. What has been demonstrated by these recent works however is what procedure to follow. First, one needs a large number of Cepheids. Second, we need to be able to separate the effects of reddening and metallicity, which tend to have almost an indistinguishable impact on a Cepheid’s energy distribution when observed through a relatively small wavelength interval; hence a large wavelength baseline is needed. Third, all Cepheids should be at the same distance to avoid introducing possible systematic errors. Fourth, Cepheids in the sample should

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cover a range of metallicities. Thus there is a need for a large-scale survey of a nearby galaxy. This will provide the needed number of Cepheids and fulfill all conditions required to address this problem.

Incidentally, lots of other things would be made possible by such a survey. Microlensing surveys have shown that completely new science can be done with very large, homogeneous samples of variable stars. For instance, large numbers of double-mode Cepheids have been found in the Magellanic Clouds (e.g. Alcock et al. (1995)). Another example is the discovery of several Period–Luminosity relations for red giants (Wood et al. (1999)). Large-scale surveys also allow us to find very rare objects, such as Cepheids in eclipsing binary systems (Alcock et al. (2002)).

Thus motivated, we started a survey of the Local Group galaxy Messier 33. It is the ideal target since it has a large metallicity gradient, is sufficiently nearby that we can obtain good-quality photometry of most Cepheids, and it has a large number of Cepheids.

Messier 33 (M 33) can be considered as one of the stepping stones of modern cosmology. It is one of the first galaxies for which Hubble obtained a distance, allowing him to show that many “nebulae” were in fact galaxies similar to our own stellar system (Hubble, 1926). A number of surveys over the next few decades found variable stars in M 33 (Hubble & Sandage (1953); van den Bergh et al. (1975)). The last major photographic survey was by Kinman, Mould and Wood (1987) who discovered 90 Cepheids, over 50 Long Period Variables, and several hundred unclassified variables. More recently the DIRECT project conducted the first CCD variability survey of M33, discovering more than a thousand variables (Macri et al. 2001; Mochejska et al. 2001a, 2001b) in the central regions of this galaxy. Shporer & Mazeh (2006) have also surveyed bright stars in M 33 over several seasons. There is also a recent multi-color CCD-based survey by Massey et al. (2006) covering a wide field. These surveys all had one or several drawbacks, however, in particular poor sensitivity (photographic), small field of view (recent CCD surveys), or too few epochs. The advent of wide-field cameras (optical and near-infrared) on 4m-class telescopes makes such a survey finally possible, without the drawbacks of previous observations.

2 The CFHT survey

We obtained data using MegaCam installed on the Canada-France-Hawai‘i Telescope. It is made of 36 2048 × 4612 CCDs, offering a one-square-degree field of view. Such a wide field covers the whole galaxy, making it ideal for this survey. We used the $g'$, $r'$ and $i'$ Sloan filters, between August 2003 and January 2005. Between 33 and 36 images have been obtained in each filter; we also have deep single-epoch $u$ and $z'$ data. Exposure times were between 8 and 11 minutes depending on the filter.

The search for variables has been described in detail in Hartman et al. (2006). We will briefly recapitulate the procedure here. The data reduction is done in two steps. First, the search for variable objects is done using the image subtraction technique, as implemented in the ISIS software (Alard and Lupton (1998)).
Fig. 1. (Left) Original image showing the level of crowding near the center of M 33. (Right) After subtraction of the reference image, only a few dozen objects are left. Note that variable objects can appear as positive (white) or negative (black) fluctuations, depending on whether the objects got brighter or fainter between the two epochs.

All images are registered to a reference image, obtained by stacking several good-seeing images. That reference image is subtracted from each program image, after matching the point-spread function and background. What is left is an image where most objects have disappeared, except those that have varied (see Fig. 1).

For each variable object, image subtraction gives the number of counts above or below the flux on the reference image. In other words, it is only a relative flux. In order to calibrate the data on an absolute flux scale, we need to do point-spread function (PSF) photometry of all sources. This is the second step of the processing. This has been done using the DAOPHOT/ALLSTAR suite of programs (Stetson 1987, 1992). The photometry was done on the reference image in each filter. Variable objects found with ISIS were matched to point sources detected by DAOPHOT so that we can eventually obtain a magnitude for each variable source.

At the present time we do not have an accurate photometric calibration. We can, however, use the default calibration provided by the observatory. This gives us a reasonably good idea of stars’ magnitudes and colors. Knowing that, we can plot color-magnitude diagrams (CMD), emphasizing the positions of variable objects (see Fig. 2).

3 Variable stars

In total we have more than 36000 variable objects. We performed rough searches for known categories of variables. Several regions have been cut out of the HR
Fig. 2. (Bottom) Color-magnitude diagrams based on photometry of the deep reference frames (grey scale). The contours indicate the density of variables. (Top) CMDs with variable stars only. They are concentrated in several areas, most noticeably the main sequence, the Cepheid instability strip, the tip of the red giant branch, the asymptotic giant branch, and the red supergiant region.

Statistics of variable stars in M 33

| Type           | Number |
|----------------|--------|
| Blue supergiants | 392    |
| Red supergiants | 984    |
| LPVs           | 19767  |
| Cepheids       | 2327   |

diagram, where we expect to find variable stars. These are blue supergiant variables, red supergiant variables, Long Period Variables (LPVs), and Cepheids. The number of objects in each group are given in Table 3.

Note that there are thousands of other variable objects that are not in any of these categories. As expected from inspection of Fig. 2, LPVs represent the majority of all variable stars. The fraction of variable objects on the asymptotic giant branch is very large; actually in some limited magnitude range the majority of AGB stars are variable (see Hartman et al. 2006 for details, in particular their
3.1 Cepheids

The number of stars in the region of the Cepheid instability strip is 3580. However, the region defined as the Cepheid instability strip in Hartman et al. (2006) is broad enough that it will necessarily contain non-variable stars. It will also contain luminous main sequence objects affected by strong reddening. A substantial fraction do not show any periodicity in the data, ruling them out as Cepheids. This is why the number of genuine Cepheids is smaller than 3580. The obvious discriminant between Cepheids and other types of stars is the period. A search for periodicity has been done using the analysis of variance method (Schwarzenberg-Czerny 1996). In total, 2011 stars have a robust period and can be considered as genuine Cepheids. There is a number of objects (a few hundreds) that are very good candidate Cepheids but for which the period search didn’t return a single, clear period. The total number of Cepheids is going to slightly increase as we refine the analysis.

We then fitted Fourier series to the light curves. The Fourier parameters (see Simon & Lee, 1981, for definition) are not very precise owing to the limited number of epochs. Nevertheless, one can clearly recognize the pulsation mode for the majority of Cepheids. According to the Fourier parameters (and to the position on the PL diagram, see below), there are 1580 fundamental-mode pulsators, and 431 overtones.

3.2 The metallicity of M 33

M 33 was initially chosen because of its large metallicity gradient. Recent measurements of the oxygen abundance [O/H] in Hii regions yield a conflicting result (e.g. Crockett et al. 2006). Cepheids themselves offer ways to constrain the metallicity of the young stellar populations. The most effective way is through double mode Cepheids. The period ratio of beat Cepheids is very sensitive to the metal content, as is known from analysis of beat Cepheids in the Magellanic Clouds (e.g. Alcock et al. 1995). Even with only ~ 35 epochs, it proved possible to find five double-mode Cepheids. A pulsation analysis of these five beat Cepheids shows that there is a strong metallicity gradient (Beaulieu et al. 2006). A large gradient is the only way to reconcile predictions of stellar pulsation theory with the physical locations of beat Cepheids in M 33.

Metallicity also affects the Cepheid period distribution, in the sense that as [O/H] goes down, the peak of the Cepheid period distribution moves to shorter periods. A plot of the Cepheid period histogram (Fig 3) clearly shows this.

3.3 Period–Luminosity relation

We need to emphasize the fact that the photometric calibration is to be taken as temporary. We have noticed significant differences in photometric zero point from
Fig. 3. Period distributions in three radial zones. The peak of the distribution is shifted to shorter and shorter periods as one gets to larger and larger radii (from top to bottom). This is a clear effect of a large metallicity gradient.

CCD to CCD and it would be dangerous to use these data if a robust zero point is needed (in particular for distance scale work). We are currently in the process of acquiring calibration data in the Sloan filters and in $UBVRI$. This will allow us to calibrate the CFHT data and also to produce Sloan-to-$UBVRI$ transformations adequate for Cepheids. This being said, the calibration is already good enough for the Period–Luminosity relation to show clearly the two sequences expected for fundamental-mode and first overtone pulsators respectively (see Fig 4).

4 Beyond a survey

While this survey is motivated by the effect of metallicity on the Cepheids PL relation, most variable objects are not Cepheids: the majority of variables are red giants. While we do not have at present enough data to find periods for LPVs, we plan to add more data so we can determine periods for these stars. This would greatly enhance the legacy value of the survey.
Fig. 4. Period-Luminosity relations in $g'r'i'$ filters. One can clearly distinguish the fundamental and first overtone sequences. We can also see a few Population II variables.

These data can also be useful for very rare objects. The candidate black hole binary M 33 X-7 is visible in our data, and its light curve has already been analyzed by Shporer et al. (2007).

M 33 has also been surveyed at other wavelengths (Spitzer, Chandra, XMM) and results have appeared recently (e.g. McQuinn et al 2007; Grimm et al. 2005). Cross-correlation of the various catalogs of objects at different wavelengths, coupled with variability information, opens a new way of studying stellar populations in nearby galaxies.

Finally, we note that all the information contained in the tables in Hartman et al. (2006) is publicly available. This web site is kept up to date regarding the calibration and the progress of the analysis.

1http://www.astro.livjm.ac.uk/~dfb/M33/
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