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The Inhomogeneous Effect of Cloud on CSTAR Photometry and Its Correction

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ABSTRACT. In 2008 January, the Chinese Small Telescope ARray (CSTAR) was successfully deployed at Dome A, Antarctica. Four identical 14.5 cm telescopes were locked pointing at the same $4.5^\circ \times 4.5^\circ$ field which contains the south celestial pole. During 4 months of continuous observations in the polar night of 2008, about 0.3 million *i*-band images were obtained. Based on these data, the first version of the photometric catalog was released without consideration for the unevenness of extinction over so large a field of view (FOV). To improve the photometric quality, we assess and correct the effect of the unevenness of extinction across the CSTAR FOV and then update the CSTAR catalog with higher photometric precision. We also discuss the reason and the statistical results of the unevenness of extinction to offer a further indication of site conditions of Dome A.

1. INTRODUCTION

High-quality, long-baseline uninterrupted time-series photometry has great significance in a large range of astrophysical problems, such as the search for transiting exoplanets and the study of variable stars. This kind of observation can be achieved most effectively by ambitious space-based programs such as *CoRoT* (Boisnard & Auvergne 2006) and *Kepler* (Borucki et al. 2010). However, the Antarctic Plateau offers a potentially comparable alternative with significantly lower costs.

The Antarctic Plateau provides unmatched conditions for a wide and diverse range of astronomical observations, including time-series photometry. Thanks to the extremely cold, dry, calm atmosphere and thin turbulent surface boundary layer, as well as the absence of light and air pollution, we can obtain a low-infrared background, new observation windows, and high-quality photometric images from the Antarctic Plateau (Burton 2010). Furthermore, the long polar night in Antarctica offers an opportunity to obtain long and continuous photometric sequences. Additionally, decreased high-altitude turbulence will result in reduced scintillation noise that will lead to superior photometric precision (Keyon et al. 2006).

In order to take the advantage of observing conditions at the Antarctic Plateau, some photometric experiments have been conducted at the different sites there. At the South Pole, SPOT, a 5-cm optical telescope, has obtained an approximately week-long continuous light curve of the Wolf-Rayet star γ^2 Velorum (Taylor 1990). At Dome C, using a small-IRAIT telescope with a 25-cm aperture, Strassmeier et al. (2008) obtained continuous

light curves for two bright variable stars over 10 days. Its photometric precision reached 3 mmag in the *V* band and 4 mmag in the *R* band for a 2.4-hr subset of the data. The precision is 3–4 times better than data from an equivalent telescope in southern Arizona. ASTEP-South, another telescope at Dome C, with a 10-cm aperture, obtained 4 months of photometric data which also shows better site conditions than temperate sites (Crouzet et al. 2010).

Dome A, located at latitude $83^\circ 7'S$ and longitude $77^\circ 53'E$, with surface elevation about 4093 m, is the highest astronomical site in Antarctica. It is also considered to be the potentially coldest place in the world (Saunders et al. 2009). After comparing with other Antarctic sites in weather, atmosphere, sky brightness conditions, Saunders et al. (2009) concluded that Dome A might be the best existing astronomical site on Earth.

The Chinese Small Telescope ARray (CSTAR) instrument was shipped and deployed at Dome A in 2008 January. Like other optical telescopes in Antarctica, CSTAR undertook both site testing and science research tasks. With high-cadence observations from 2008 March 4 to 2008 August 8, about 0.3 million qualified *i*-band CCD images were acquired.

Based on these images, Zhou et al. (2010a) have released the first version of the CSTAR point source catalog of over 10,000 stars. The CSTAR data have also been successfully used to test the site characteristics of Dome A, such as the sky brightness, transparency, cloudiness and aurora (Zou et al. 2010). About 157 variable stars have been detected in CSTAR data, including those in previous catalogs. This number is 5 times as many as previous surveys with similar magnitude limits (Wang et al. 2011).

Owing to the high-quality and high-cadence photometric sequence, the data can also be used to search for the signals of transiting exoplanets. Using the transit method to detect exoplanets requires photometry with precision significantly better than the typical depth of a Jupiter-size planet transit (~ 0.01 mag).

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Successful transit surveys are typically achieving photometric precisions of 0.005 mag or better (e.g., HAT: Bakos et al. [2007], WASP: Pollacco et al. [2006]). But the current CSTAR catalog (Zhou et al. 2010a) cannot satisfy this requisite precision.

We have analyzed the potential sources of photometric errors. In addition to the statistical photometric noise of the star, several kinds of possible systematic errors can affect photometric precision, such as ghost images, undersampling of the CCD, and the unevenness of extinction across the large FOV. In this work, we focus on quantifying and correcting the effect of the unevenness of extinction across the CSTAR FOV. Other systematic errors will be corrected in future work.

When the star light passes through the atmosphere, because of the scattering and absorption effects, the stellar radiation will be attenuated. This is called the “atmospheric extinction,” which includes the effect of the optical thickness of the cloud cover. Ideally, if the atmospheric extinction is uniform across the FOV or if any kinds of cloud are absent, we can obtain the true flux of all the sources by calibrating to a single standard. But according to Zou et al. (2010), a part of CSTAR images were affected by cloud. Because CSTAR gives about 20 square degrees FOV, we cannot assume the cloud is uniform over so large a FOV. A flux calibration with a single value in an image will cause some errors when the image is affected by the uneven cloud. Due to the varying extinction over the FOV, a different calibration is required for each star in the same image.

In order to reduce this kind of systematic error, we first make a reference catalog from over 10,000 published catalogs under good photometric conditions (Zhou et al. 2010a). The reference catalog contains the mean magnitude and mean position of every star in the CSTAR FOV. Then, we compare an ensemble of the detected magnitudes of the bright and unsaturated stars in the published catalog (Zhou et al. 2010a) with their magnitudes in the reference catalog. With the obtained distribution of magnitude difference (which infers the cloud structure), we update the published catalog and discuss the statistical results of the unevenness of transparency to offer a further indication of site conditions of Dome A.

This article is organized as follows. We describe the observations and previous data reduction of CSTAR images in § 2. The reference catalog of all the stars in the CSTAR FOV is presented in § 3. Then, we give the method for assessment of the cloud structure and catalog correction in § 4. In § 5, we analyze and discuss our results. Finally, we make a conclusion of the work in § 6.

2. OBSERVATIONS AND PREVIOUS DATA REDUCTION

2.1. CSTAR Instrument

The CSTAR telescope array consists of four identical Schmidt telescopes with the same 20-deg² (4.5° × 4.5°) FOV

centered on the south celestial pole. Each telescope gives a 145-mm entrance pupil diameter (effective aperture of 100 mm) and has a different filter: *i*, *g*, *r* and open. The focal plane of each telescope is equipped with a 1 K × 1 K Andor DV 435 frame transfer CCD array, with pixel size 13 μm and plate scale 15"/pixel. As the first Chinese Antarctic telescope, CSTAR was designed to be totally fixed, without any moving parts. The details of the CSTAR instrument are given in Yuan et al. (2008) and Zhou et al. (2010b).

Before being shipped to Antarctica, the CSTAR data acquisition system was tested in low temperature in a laboratory refrigerator and low pressure on the 4500 m Pamirs Plateau. The complete CSTAR instrument also had test observations at NAOC's Xinglong Observatory. Test details are presented in Zhou et al. (2010b).

2.2. Observations

In 2008 January, after being effectively and extensively tested, CSTAR was deployed at Dome A as a part of the PLATEAU Observatory (PLATO) (Yang et al. 2009; Lawrence et al. 2009), which provides power, heat, and an internet connection for CSTAR. Although some problems prevented us from obtaining useful data in *g*, *r*, and the open filter, fortunately, in the *i*-band, the observations were successfully conducted during the polar night of 2008 (from 2008 March 4 to August 8). About 0.3 million images were obtained with a 20-s exposure time, and about 1728-hr exposure time in total. In good photometric conditions, more than 10,000 sources down to *i* = 16 could be detected (Zhou et al. 2010a). The CSTAR instrument has been running for the past 4 years (2008, 2009, 2010, and 2011); our current work is based on the data from 2008.

2.3. Previous Data Reduction

After obtaining high-quality images from the CSTAR telescope in 2008, two groups presented their independent results of data analysis. Zhou et al. (2010a) published the catalog of all the sources. Wang et al. (2011) announced 157 variable stars, including those in previous catalogs. In this article, our work is based on the results of Zhou et al. (2010a).

We briefly review their technique here. In that work, because there were no realtime flat-field images, a special flat-field method was applied to all the images. After preliminary reduction, aperture photometry was conducted to derive the instrumental magnitude of sources in each image with three different aperture radii: 3, 4 and 5 pixel (or 45", 60" and 75"). Then an image (A5CH5029) under good photometric conditions was chosen as a standard image to calibrate other images. For the other images, they compared the brightness of selected bright stars with the ones in the standard image, thus deriving a mean magnitude offset for each image. This offset was then applied to all the stars on the image. The magnitude was finally linked to the USNO-B 1.0 photometric system by the 48

brightest stars within the CSTAR FOV, and a catalog of more than 10,000 stars was released (Zhou et al. 2010a).

3. THE REFERENCE CATALOG

As described above, in order to assess and reduce the possible systematic errors caused by uneven cloud in the published catalog, we first create a reference catalog. We select over 10,000 published catalogs (Zhou et al. 2010a) under the best photometric conditions. These catalogs contain all the stars within the CSTAR FOV. For each star, we derive its mean magnitude and mean position from these catalogs with a 3σ clip. Finally, we get a reference catalog that contains all about 21,000 objects within the CSTAR FOV.

It should be noted that “the position of a star” here refers to the position of the star in the coordinate system of the standard image. Because the totally fixed CSTAR telescope is pointed at the south celestial pole, diurnal motion can be seen in CSTAR FOV. Each star has a different position in different images. To identify the stars, the position of each star in each image has been converted to the coordinate system of the standard image (A5CH5029) (Zhou et al. 2010a).

The mean magnitude of each star in the reference catalog is derived from over 10,000 catalogs under the best photometric conditions. Hence, they possess extremely low photometric errors. Figure 1 shows the statistical error distribution as a function of mean magnitude in the reference catalog. For an

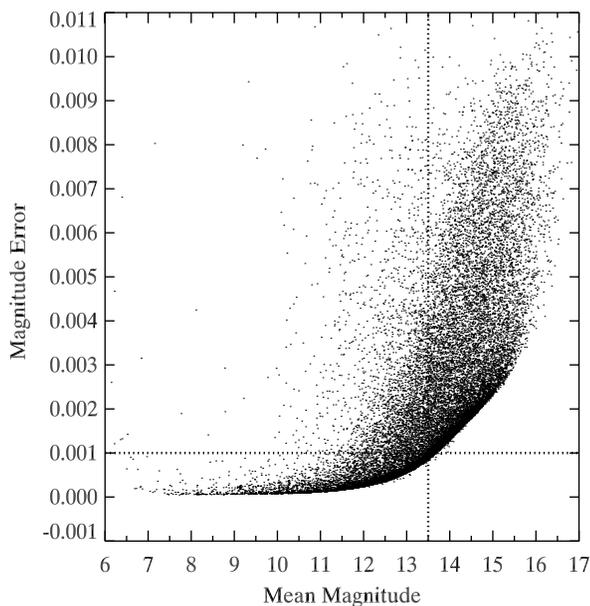


FIG. 1.—Error distribution of the mean magnitude of every star in the reference catalog. All the stars in the reference catalog show extremely low photometric errors. For an $i = 13.5$ star, the modal value of photometric error is about 0.001 (dotted line).

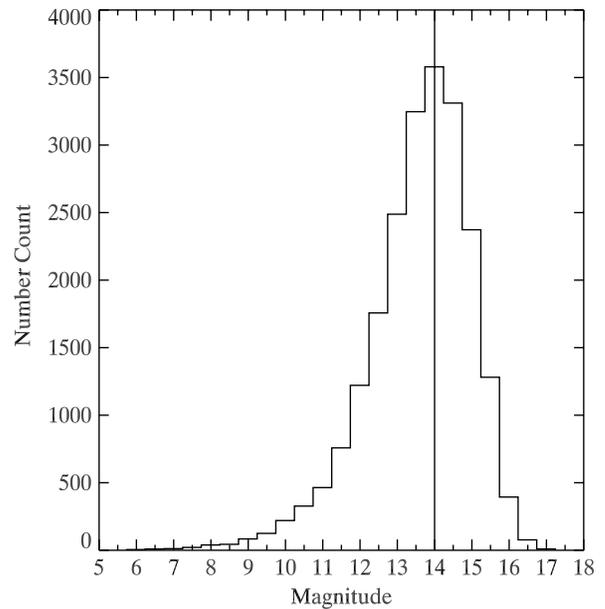


FIG. 2.—The histogram of mean magnitude in the reference catalog. The reference catalog is complete to $i = 14$.

$i = 13.5$ star, the modal value of statistic error is just about 0.001. With a bin size of 0.5 mag, we obtain the histogram of the mean magnitude in the reference catalog, as shown in Figure 2. The reference catalog is considered to be complete to $i = 14$.

4. THE CORRECTION OF THE CLOUD STRUCTURE

After obtaining the reference catalog, we compare an ensemble of the magnitude of the selected stars in each published catalog with their magnitude in the reference catalog to look at the distribution of magnitude difference in each frame. This distribution of magnitude difference infers the cloud structure across the FOV at the time when the image was taken.

The concrete method of obtaining and reducing the cloud structure across each frame comprises the following steps:

1. *The selection of the stars.* In order to ensure the accuracy of the correction, the bright and unsaturated ($i = 7.0\text{--}13.5$) stars in each published catalog with photometric error less than 0.3 are selected. Due to the varying photometric conditions, the number of the selected stars (represented by N below) is different in different catalogs.

2. *Individual magnitude differences.* For each frame, we can obtain the magnitude differences (represented by δmag_i below, where $i = 1, 2, \dots, N$) at the position of the selected stars (represented by ‘+’ symbols in Figs. 3 and 4). The magnitude differences are the magnitude of the selected stars in the published

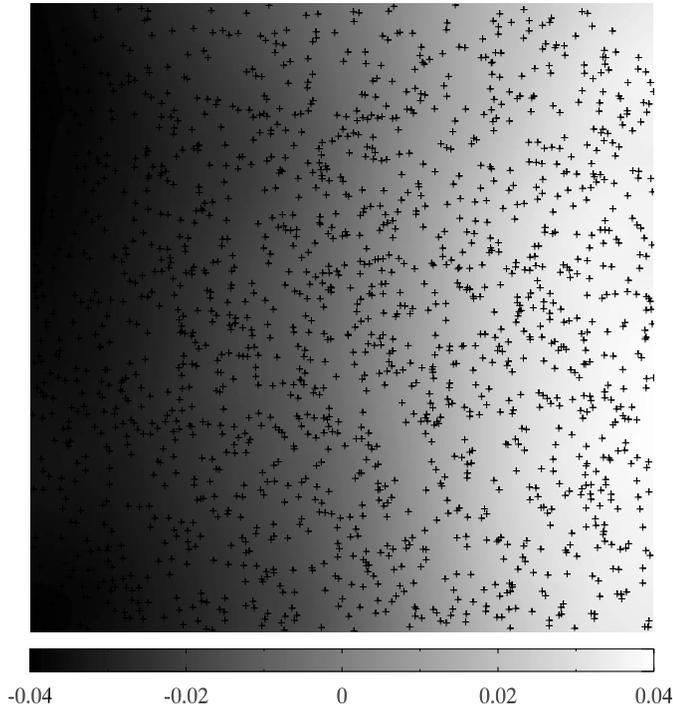


FIG. 3.—The cloud structure of an image (A68F2318) taken in poor photometric conditions. In the figure, the ‘+’ symbols indicate the position of the selected stars which are used to calculate the magnitude differences between the published catalog and the reference catalog. The grayscale denotes the structure of the cloud. The gray is varying from black at the thinnest cloud to white at the thickest cloud.

catalog (mag_i) minus their magnitude in the reference catalog (mag_{0i}):

$$\delta\text{mag}_i = \text{mag}_i - \text{mag}_{0i}, \quad i = 1, 2, \dots, N. \quad (1)$$

Therefore, if a magnitude difference is positive, the corresponding star in the published catalog is fainter than it is in the reference catalog. The additional extinction should be caused by the thick cloud. It suggests that the cloud at the position of the star is thicker than the mean thickness of the cloud over the FOV. Conversely, if a magnitude difference is negative, that means the cloud in this position is thinner than the mean thickness of the cloud over the FOV.

3. *Interpolation.* To obtain the smooth cloud structure of a frame, the interpolation of the magnitude difference in each pixel can be calculated by all of the individual magnitude differences in the image. The interpolation of the j th ($j = 1, 2, \dots, M$, $M = 1024 \times 1024$) pixel in a frame is related with two factors. One is the distance (represented by d_{ij} below) between the i th individual magnitude difference and the j th pixel. The other is the error (represented by σ_i below) of the i th individual magnitude difference. The closer and higher accuracy individual magnitude difference has the greater effect on the interpolation of

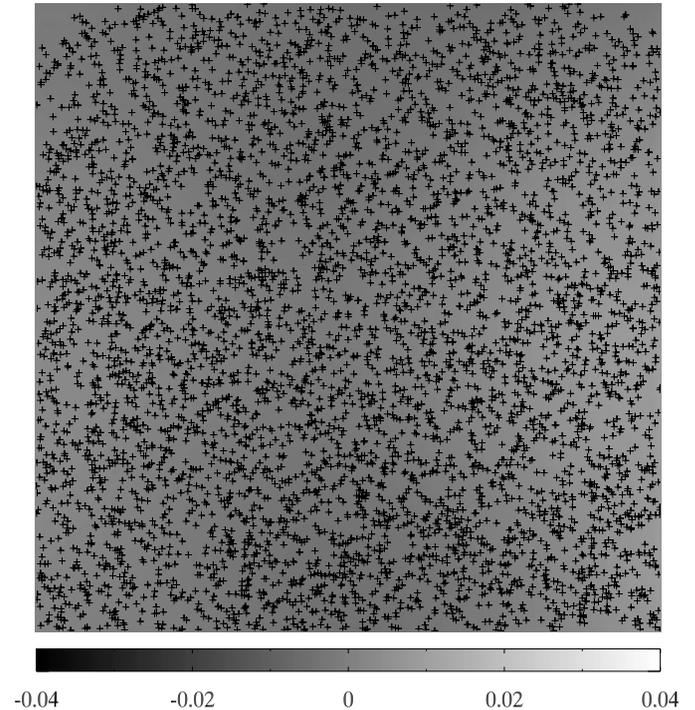


FIG. 4.—Same as Figure 3, but for an image (A6134704) taken in good photometric conditions. The symbols have the same meaning.

the pixel. The interpolation of the j th pixel (represented by $\Delta\overline{\text{mag}}_j$ below) in a frame can be calculated by:

$$\Delta\overline{\text{mag}}_j = \frac{\sum_{i=1}^N P_{ij} \delta\text{mag}_i}{\sum_{i=1}^N P_{ij}}, \quad j = 1, 2, \dots, M, \quad (2)$$

$$M = 1024 \times 1024,$$

where $\Delta\overline{\text{mag}}_j$ is the interpolation of the j th pixel in the frame, N is the number of those individual magnitude differences, which equals to the number of selected stars in the frame, δmag_i is the i th individual magnitude difference in the frame, and P_{ij} is the weight of δmag_i relative to the j th pixel:

$$P_{ij} = \frac{e^{C d_{ij}}}{\sigma_i^2}. \quad (3)$$

Here, d_{ij} denotes the relative distance between the i th individual magnitude difference and the j th pixel, σ_i is the error of the i th individual magnitude difference, which can be represented by the photometric error of the corresponding star, and C is:

$$C = -0.31 \frac{\sqrt{N}}{N_{\text{ccd}}}, \quad (4)$$

where N still means the number of the selected stars, $N_{\text{ccd}} = 1024$ is the size of the CCD in pixels, and -0.31 is a constant

that optimized the range affected by an individual magnitude difference.

In this way, we can derive the interpolation of the magnitude difference at each pixel in each frame. This represents the cloud structure over the frame.

4. *Catalog correction.* After obtaining the cloud structure over each frame, we correct its effect in each corresponding catalog. For each star, we derived its corrected magnitude by subtracting the magnitude difference of the corresponding position in the frame.

Here we give two examples to illustrate the cloud structure under both good and bad photometric conditions. In image A68F2318, the photometric condition is poor. Fewer stars can be used to construct the structure of the cloud ($N = 1632$). So the effective region of each selected star is large, and leads to a relatively low-resolution cloud structure (Fig. 3). However, we can see the structure of the cloud is obvious and the biggest fluctuation is up to 0.04 m.

If we examine A6134704, an image taken in good photometric conditions, a large number of stars can be selected ($N = 5197$). With them, a high-resolution cloud structure can be obtained (Fig. 4). There is no obvious cloud structure in this frame; the largest cloud fluctuation is less than 0.01 m.

5. ANALYSIS AND DISCUSSION

The cloud has continuity not only in space, but also in time. The interval between two successive CSTAR images is about 20 s. Sometimes the wind at Dome A is strong, hence, during the interval, the cloud structure over the FOV is totally changed, so we cannot find an apparent connection from the cloud structure in successive images. However, sometimes we can see the continuous movement of the cloud structure in successive images. As shown in Figure 5, we demonstrate a ~ 1 -minute series of images of cloud structure at UT15:00 on June 8. We can see an apparent cloud structure sweeping over the CCD from the lower left corner to the upper right corner in these successive images.

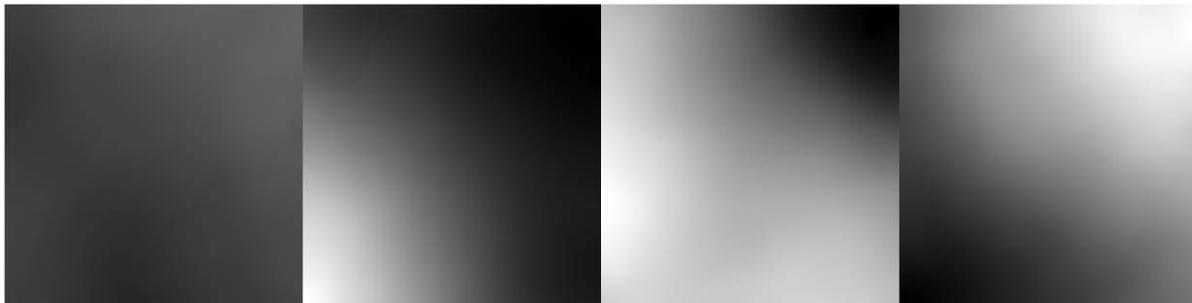


FIG. 5.—A series of continuous images of cloud structure, spanning 1 minute of observation. A piece of cloud swept over the CCD from the *lower left corner* to the *upper right corner*.

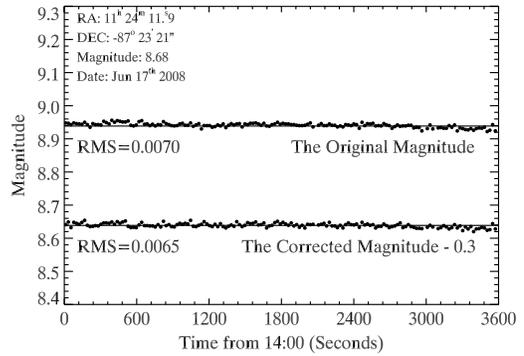


FIG. 6.—Comparison of the light curves from a series of images under good photometric conditions. The *solid lines* denote the mean magnitude of the star in the reference catalog. The cloud-corrected data are offset by 0.3 mag for clarity. From the figure we can find that the precision of the data under good photometric conditions has no obvious improvement.

The main attention in this work is concentrated on improving the photometric precision of the previous published CSTAR catalog (Zhou et al. 2010a) by correcting the unevenness of extinction. Thus, here we compare the accuracy of the light curve from the previously published CSTAR catalog and the revised catalog in both good and bad photometric conditions to show the effects of the cloud correction.

In Figure 6, we compare two light curves of a star with $i = 8.68$ in a 1-hr interval in good photometric conditions at UT14:00 on June 17. The upper light curve is that from the previously published catalog (Zhou et al. 2010a). The root mean square (rms) scatter of this part of the light curve is 0.0070. The lower one is the light curve from our newly revised catalog, and its rms is 0.0065. The accuracy of this light curve has no significant improvement. This is because in good photometric conditions, there is little cloud to influence the uniformity over the FOV.

The slight improvement of the accuracy of the light curve in good photometric conditions is considered to be the result of correcting a kind of cloud structure like what Figure 7 shows.

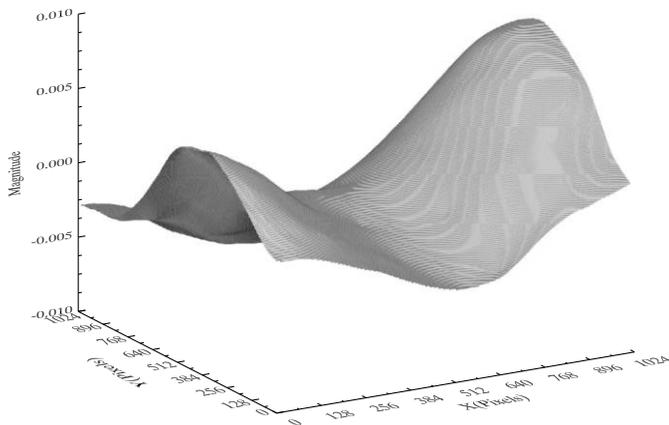


FIG. 7.—The cloud structure derived from a CSTAR image (A64E3827) under the best photometric conditions. It is considered to be the “residual flat-field” of CSTAR data. This is not only because there is no reason to cause so large unevenness of transparency in the best photometric conditions, but also because the similar structure will remain for a long time in other images taken in outstanding photometric conditions.

This structure could not be the structure of cloud, not only because the transparency across the FOV is very good and uniform in good photometric conditions, but also because the similar structure will remain for a long time in other images taken in good photometric conditions. In the first version of the catalog, all the images were reduced by a single rough flat field (Zhou et al. 2010a). So this kind of uneven structure in good photometric conditions is considered to be a ‘residual flat field’ less than 0.01 mag. As a by-product this kind of ‘residual flat field’ is also corrected in this work.

To show the effects of our correction on data in poor photometric conditions, Figure 8 shows two light curves of a star with $i = 8.36$ in a 1-hr period at UT15:00 on June 8. As in Figure 6, the upper light curve is that from the original catalog. The rms of

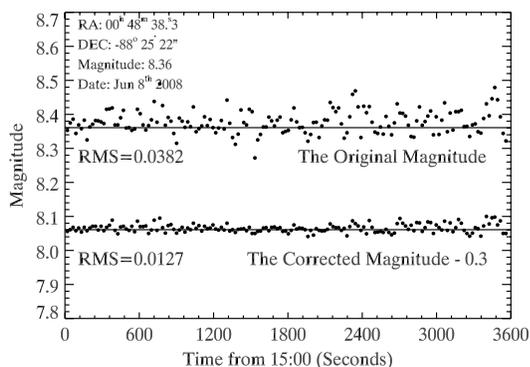


FIG. 8.—Comparison of the light curves from a series of images under poor photometric conditions. The *solid lines* denote the mean magnitude of the star in the reference catalog. The cloud-corrected data are offset by 0.3 mag for clarity. From the figure we can find that the precision of the data under poor photometric conditions has an obvious improvement.

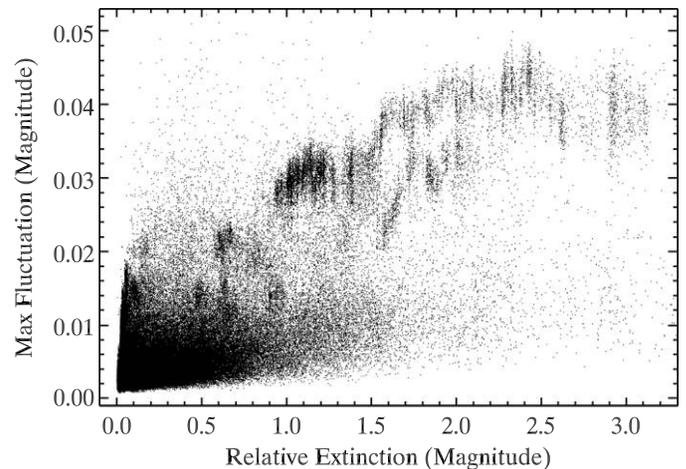


FIG. 9.—The relationship between the value of relative extinction and the unevenness of extinction at Dome A during 2008. Each point represents a frame.

this part of data is 0.0382. The lower one is the light curve from our new catalog, with the rms of 0.0127. It is clear that the precision of the light curve is significantly improved in our new catalog.

It is worth mentioning that due to its location in a special site—Dome A, Antarctica—about 2% of CSTAR photometric images were affected by relatively strong aurorae (Zou et al. 2010). Aurorae themselves will not cause any changes in the extinction, but will increase the brightness and unevenness of the sky background, which will lead to a lower photometric accuracy. So, for an image affected by the aurorae, fewer high-precision stars can be used to construct the structure of the cloud. However, the uneven extinction in the image can also be well corrected by a relatively lower-resolution cloud structure. Therefore, the accuracy of the correction can be guaranteed when the images were affected by the aurorae.

What is the relationship between the thickness and the unevenness of cloud? When we look at the unevenness of extinction in each CSTAR frame, it is natural to think about this question. In our work, the biggest fluctuation of cloud structure can be used to measure the unevenness of cloud in a frame. The relative offset in instrumental magnitude between each image and a best photometric image (A5CH5029) can be used to measure the value of relative extinction (refers to the thickness of the cloud). As shown by Figure 9, there is a clear trend that the possible unevenness in a frame increases with the value of relative extinction, because if the transparency is good enough (the relative extinction is small enough), there is no reason to cause the unevenness of transparency. It is worth noting that although frames with the lowest relative extinction show the good evenness of extinction, a part of frames with low relative extinction also show some unevenness of extinction. This may be caused by the thin, narrow, and high-contrast cirrus clouds across the CSTAR FOV. This kind of cirrus is too narrow to obviously

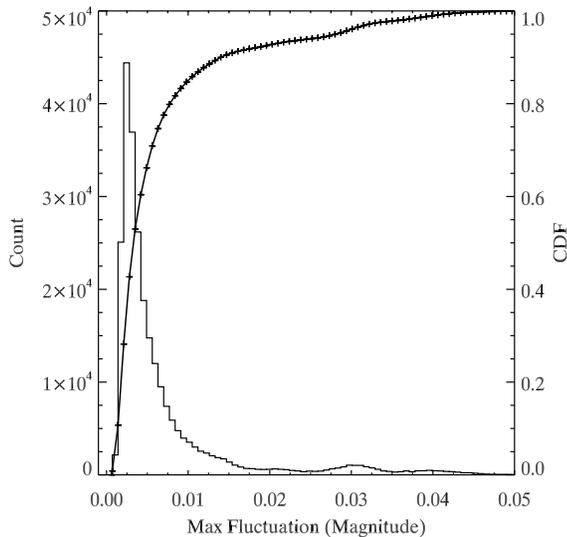


FIG. 10.—The histogram and the cumulative distribution function (CDF) of the unevenness of transparency at Dome A during 2008. The curved line marked '+' is the CDF.

influence the value of relative extinction, but it could account for the significant unevenness of extinction.

Furthermore, in the relation between the maximum fluctuation and the relative extinction (Fig. 9), there are two clear branches. The upper branch shows the unevenness of extinction obviously increasing with the value of relative extinction. It is considered to be caused by high cirrus in Dome A. This type of cloud is traveling with slower angular speed relative to the CSTAR telescope. Therefore, in a 20-s exposure, it leads to not only the value of relative extinction but also corresponding unevenness. Although the lower branch also shows a similar trend as the upper one, it is much flatter. This kind of phenomenon is believed to be a result of fast moving fog near the ground surface of Dome A. The relative angular velocity between the moving fog and CSTAR telescope is fast, so during the 20-s exposure time, the fog structure has been smoothed over all of the CSTAR FOV. Thus, it only contributes to the value of relative extinction but not the significant unevenness.

Here, because we use the biggest fluctuation of the cloud structure to infer the unevenness of transparency, our results represent the upper limits of the unevenness of the transparency in Dome A in 2008. Figure 10 shows both the histogram and the cumulative distribution function (CDF) of the unevenness of transparency at Dome A. Most images have little unevenness of transparency: about 83.7% of images were taken under even photometric conditions (the unevenness of extinction < 0.01 mag). 92.4% were affected by the unevenness less than 0.02 mag. Only about 8% of images were affected by relatively larger uneven extinction (> 0.02 mag). Therefore, during 2008, more than 80% of the observation time at Dome A was suitable for accurate photometry. However, this conclusion is tentative

due to the limited sky field of CSTAR and the fact that the Dome A data are from only about 4 months during 2008.

6. CONCLUSION

The advantage of the Antarctic Plateau for a wide and diverse range of astronomical observations can scarcely be exaggerated. It provides preeminent observation conditions not only for infrared, terahertz, and submillimeter astronomy, but also for optical astronomy. The long polar night together with the excellent photometric conditions in Antarctica also offer opportunities for continuous time-series photometry.

Dome A, with the more extreme conditions, is considered as likely the best existing astronomical site on Earth. To test the characteristics of site at Dome A and to search for variable objects such as variable stars and transiting exoplanet systems, in 2008 January the CSTAR telescope array was successfully deployed at Dome A. CSTAR, with the large FOV (about 20 deg^2) and four different filters (*i*, *g*, *r* and open), was locked pointing to a fixed patch of the sky, which contains the south celestial pole. After 4 months of observations in 2008, about 0.3 million qualified images with 20-s exposure were obtained. Based on these data, the first version of CSTAR catalog was released (Zhou et al. 2010a).

To give the higher precision of CSTAR catalog required by the transiting exoplanet search, we assess and correct the unevenness of extinction across the large CSTAR FOV. The new version of catalog is available online.³ As a good by-product, we correct the “residual flat-field” in the data as well. As another intermediate product, we also release a reference catalog which gives the mean magnitudes of every star within CSTAR FOV. Because the reference catalog is reduced from more than 10,000 best published photometric catalogs, it shows extremely low statistical errors. Therefore, it can be considered as the most accurate magnitude catalog of all the stars in this area of the sky. The reference catalog is also available online.⁴

The atmospheric extinction at Dome A is considered to be caused by both the high cirrus and the fog near the ground surface. Because the high cirrus has lower angular speed relative to the telescope, its structure could not be smoothed over all of CSTAR FOV. The unevenness of extinction across the FOV is believed to be mainly caused by the high cirrus. Although there is inevitable cloud at Dome A, the statistical results of our study show that even transparency is found in 83.7% of CSTAR images. Hence, more than 80% of observation time at Dome A during 2008 was suitable for accurate photometry.

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³ See <http://casdc.china-vo.org/data/cstar>.

⁴ See <http://casdc.china-vo.org/data/cstar>.

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