Astrophysics from Antarctica
Proceedings IAU Symposium No. 288, 2012
M. G. Burton, X. Cui & N. F. H. Tothill, eds.

doi:10.1017/S1743921312016936

Progress and Results from the Chinese Small Telescope ARray (CSTAR)

Xu Zhou[1,5], M. C. B. Ashley[4], Xiangqun Cui[2,5], Longlong Feng[3,5], Xuefei Gong[2,5], Jingyao Hu[1,5], Zhaoji Jiang[1,5], C. A. Kulesa[8], J. S. Lawrence[4,6], Genrong Liu[2], D. M. Luong-Van[4], Jun Ma[1], Lucas M. Macri[1,4], Zeyang Meng[15], A. M. Moore[9], Weijia Qin[7], Zhaohui Shang[10], J. W. V. Storey[4], Bo Sun,[7], T. Travouillon[9], C. K. Walker[8], Jiali Wang[1,5], Lifan Wang[3,5], Lingzhi Wang[1],[14], Songhu Wang[15], Jianghua Wu[1], Zhenyu Wu[1], Lirong Xia[2], Jun Yan[1],[5], Ji Yang[3], Huigen Yang[7], Yongqiang Yao[1], Xiangyan Yuan[2,5], D. York[11], Hui Zhang[15], Zhanhai Zhang[7], Jilin Zhou[15], Zhenxi Zhu[3,5] and Hu Zou[1]

[1]National Astronomical Observatories, Chinese Academy of Sciences, Beijing, 100012, China; zhouxu@bao.ac.cn

[2]Nanjing Institute of Astronomical Optics and Technology, Nanjing 210042, China

[3]Purple Mountain Observatory, Nanjing 210008, China

[4]School of Physics, University of New South Wales, Sydney NSW 2052, Australia

[5]Chinese Center for Antarctic Astronomy

[6]Macquarie University & Anglo-Australian Observatory

[7]Polar Research Institute of China, Pudong, Shanghai 200136, China

[8]Steward Observatory, University of Arizona, Tucson, AZ 85721 USA

[9]Department of Astronomy, California Institute of Technology, Pasadena CA 91125, USA

[10]Tianjin Normal University, Tianjin 300074, China

[11]Department of Astronomy and Astrophysics and Enrico Fermi Institute, University of Chicago, Chicago IL 60637, USA

[12]Graduate University of Chinese Academy of Sciences, Beijing 100049, China

[13] Department of Astronomy, Beijing Normal University, Beijing, 100875, China

[14] Mitchell Institute for Fundamental Physics & Astronomy, Department of Physics & Astronomy, Texas A&M University, College Station TX 77843, USA

[15] Department of Astronomy & Key Laboratory of Modern Astronomy and Astrophysics in Ministry of Education, Nanjing University, Nanjing 210093, China

Abstract. In 2008 January the 24th Chinese expedition team successfully deployed the Chinese Small Telescope ARray (CSTAR) to Dome A, the highest point on the Antarctic plateau. CSTAR consists of four 14.5 cm optical telescopes, each with a different filter (g, r, i and open) and has a $4.5° \times 4.5°$ field of view (FOV). Based on the CSTAR data, initial statistics of astronomical observational site quality and light curves of variable objects were obtained. To reach higher photometric quality, we are continuing to work to overcome the effects of uneven cirrus cloud cirrus, optical "ghosts" and intra-pixel sensitivity. The snow surface stability is also tested for further astronomical observational instrument and for glaciology studies.

Due to the extremely cold, dry, calm, thin atmosphere and 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). Over the long polar night, the observation of high quality, long-baseline uninterrupted time-series photometry has great significance to 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 can offer a comparable alternative with significantly lower costs.

The successful site testing and astronomical observations at Dome C (Crouzet *et al.* 2010) encourage astronomers to think about the observational conditions of Dome A. Dome A, located at latitude $80°37'$ S and longitude $77°53'$ E, with surface elevation about 4,093 m, is the highest astronomical site in Antarctica. It is also considered to be the potential coldest place in the world (Saunders *et al.* 2009). After comparing with other Antarctic sites in weather, atmosphere, sky brightness condition, Saunders *et al.* (2009) concluded that Dome A might be the best of the existing astronomical sites on Earth.

The Chinese Small Telescope ARray (CSTAR) was developed for site testing and installed at Dome A in 2008 January. Like other optical telescopes in Antarctica, CSTAR undertook both site testing and science research tasks. CSTAR includes 4 small telescopes with apertures of 14.5 cm in diameter. Three of the telescopes are covered with SDSS g, r and i band filters and one has no filter. CSTAR is mounted on a tripod, with fixed pointing at the south polar sky field. Andor 1K$\times$1K frame transfer CCD cameras are used. There is no any mechanical moving part in the whole observational system. Parts of CSTAR have operated well for the last 5 years (from 2008). One telescope of CSTAR was brought back in 2010 and the whole instrument was dismounted in 2012 January for system optimization.

With high-cadence observations from 2008 to 2011, about 2.5 TB of image data were obtained. Fig. 1 to Fig. 3 show the daily image count of observation seasons from 2008 to 2010.

Based on the data from 2008, Zhou *et al.* (2010a) released the first version of the CSTAR point source catalog of over 10,000 stars, updated recently to a magnitude limit of 14 in i band (S. H. Wang *et al.* 2012). The CSTAR data have already been successfully used to test the site characteristics of Dome A (Zou *et al.* 2010), for detection of the variable stars (Wang *et al.* 2011), and to study the stability of the snow surface of Dome A.

By comparing the catalog of each image with the catalog of mean magnitude and mean position of stars as reference, the statistics of the sky brightness, atmospheric transparency and appearances of the aurora are obtained. As a result for the overall night sky, a median brightness of 19.8 mag arcsec^{-2} is found across all lunar phases (left panel in Fig. 4). A median of 20.5 mag arcsec^{-2} is found for moonless clear nights (right panel of Fig. 4). Dome A has a darker sky background than the other Antarctic astronomical sites, even allowing for calibration and other uncertainties of up to several tenths of a magnitude (Zou *et al.* 2010).

In the atmospheric extinction distribution of 2008, as shown in Fig. 5, 90% of the images show an extinction of less than 0.7 mag, 80% less than 0.4 mag and more than half of the time, the extinction is less than 0.1 mag. The monthly variation of observational qualities shows that the weather is relatively bad in the second half of the 2008 and 2010 winters.

Because the variation of the sky transparency depends on the cloud coverage, it is well-correlated to the sky brightness. The sky brightness can also be well calculated with the parameters of Sun and Moon elevation, Moon phase and atmospheric extinction:

$$F_{sky} = a(F_{sun} + F_{moon})E + bE + c$$

https://doi.org/10.1017/S1743921312016936 Published online by Cambridge University Press

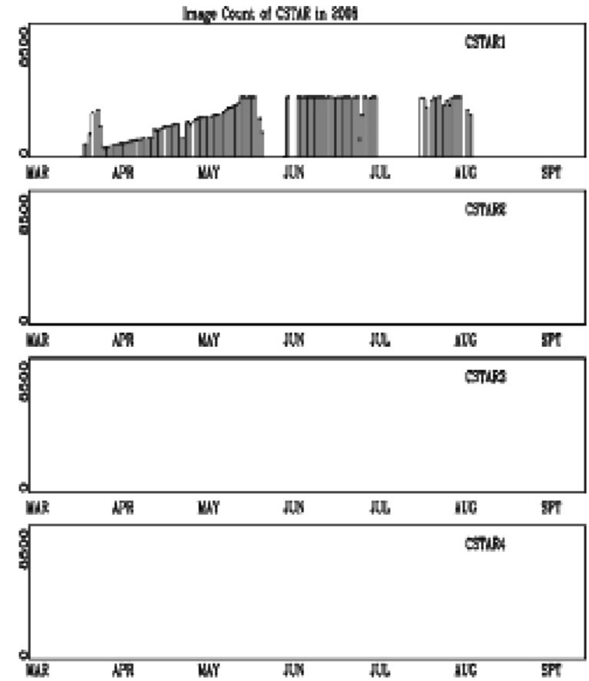

Figure 1. The daily image count of observations in 2008 from the 4 different CSTAR telescopes.

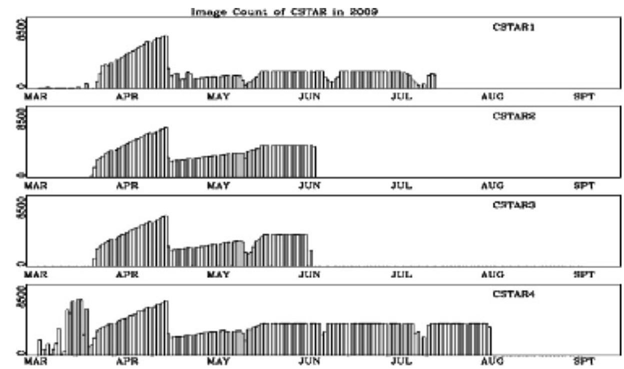

Figure 2. As Fig. 1, but for 2009.

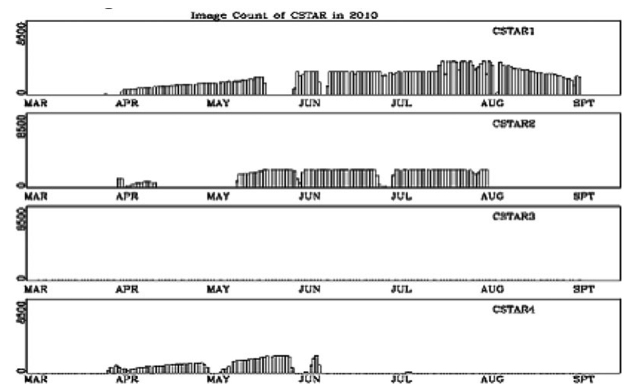

Figure 3. As Figs. 1 & 2, but for 2010.

https://doi.org/10.1017/S1743921312016936 Published online by Cambridge University Press

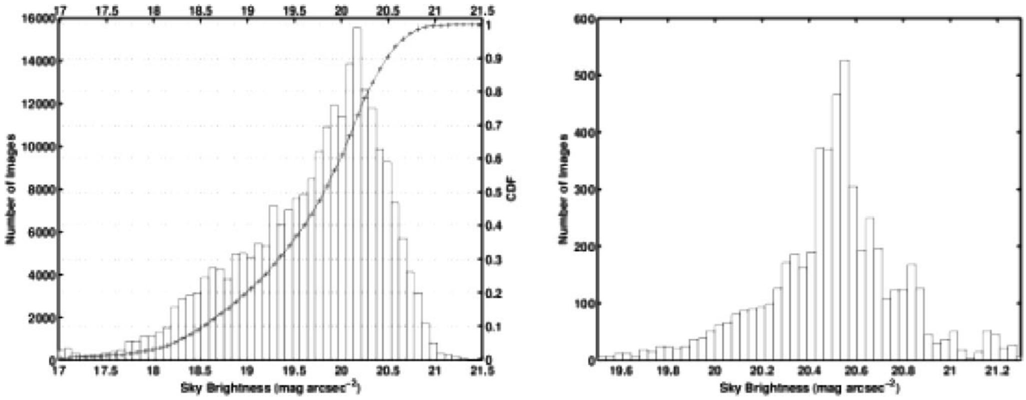

Figure 4. Left panel: Histogram and cumulative distribution function (CDF) of the i-band sky brightness distribution at Dome A during 2008. Right panel: Same information for the subset of images taken on moonless clear nights in 2008 June.

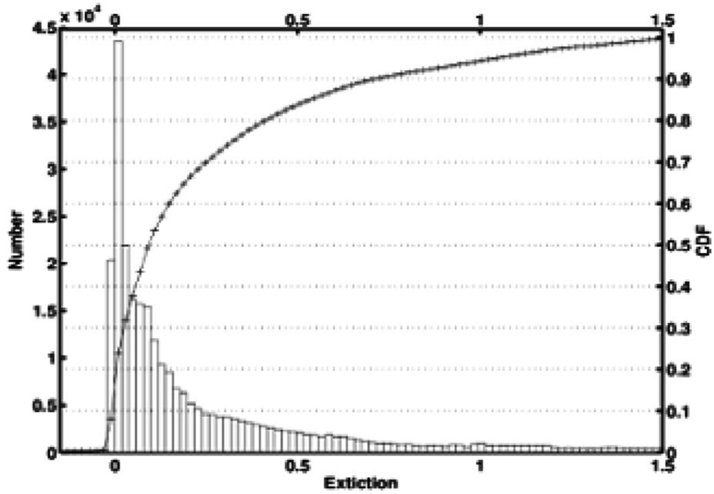

Figure 5. Histogram of the number of images with given transparency variation (in magnitudes) relative to the reference image. The curved line marked '+' is the CDF.

Here, $F_{sun} + F_{moon}$ are the solar and lunar contributions and E is transparency. a, b and c are parameters obtained from fitting.

The above relation is obtained from images without auroral pollution. The real sky brightness may be brighter than estimated. Outliers outside 3 times the rms should be considered as relatively strong aurorae. About 2% of images are affected by aurorae (Zou *et al.* 2010).

Wang *et al.* (2011) have done independent photometry on the CSTAR images to search for variable stars. In the inner circle of the CCD FOV, they found 157 variable sources from images taken in 2008, about 5 times as many as previous surveys with similar magnitude limits. Fig. 6 shows an example light curve of a contact binary. Furthermore, they analysed the data in the full CSTAR sky coverage field and found 113 new variable candidates from the CSTAR data of 2010 (L. Z. Wang *et al.* 2012).

The ongoing instrument plans are to change the CSTAR mount to that of a normal telescope, adjusting optics and improving the hardware and software of CCD control system. We plan to continue scientific research on object variation, searching for extra-solar

https://doi.org/10.1017/S1743921312016936 Published online by Cambridge University Press

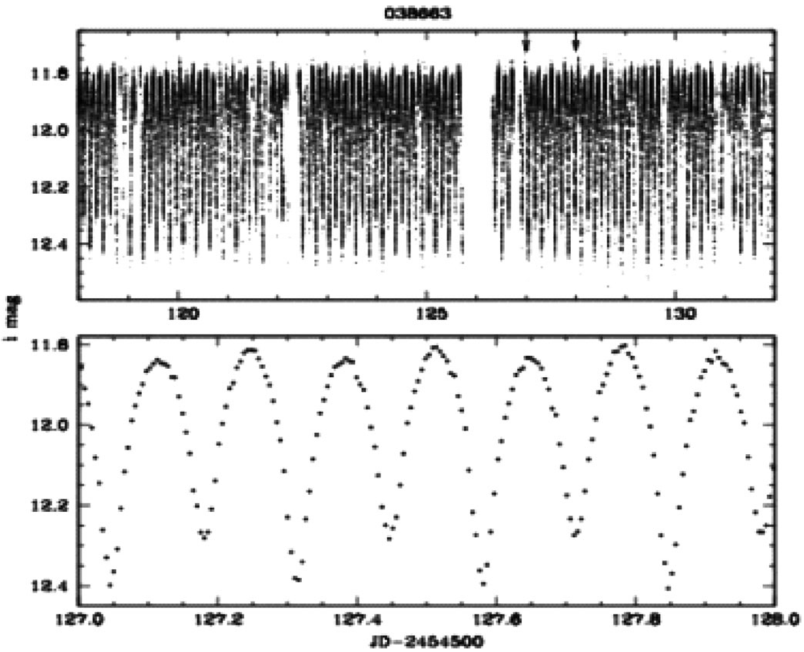

Figure 6. Time-series light curve of a contact binary in the CSTAR FOV. Only a small fraction of the complete CSTAR data is shown. Top panel: Light curve sampled at 20s intervals. Bottom panel: a portion of the top light curve (bounded by the arrows) binned into 450s intervals.

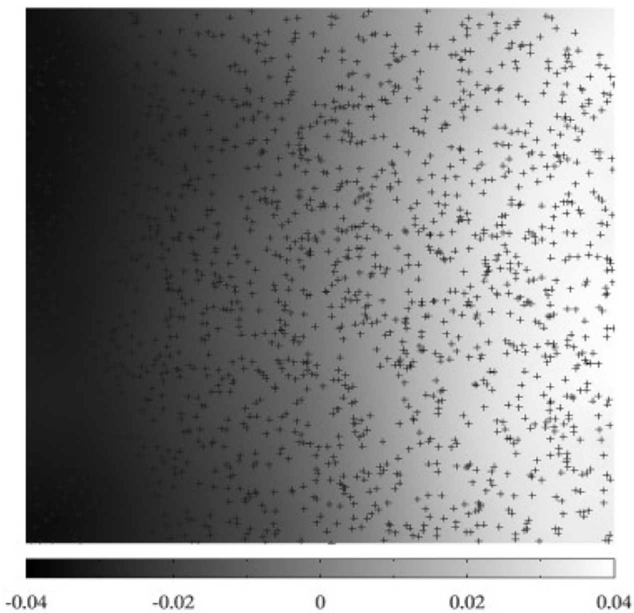

Figure 7. The cloud (extinction difference in magnitude) structure of an image (A68F2318) taken in poor photometric conditions. The grayscale denotes the structure of the cloud. '+' indicate positions of the selected stars used to calculate magnitude differences between the published catalog and the reference catalog; black is the thinnest cloud and white is the thickest cloud.

https://doi.org/10.1017/S1743921312016936 Published online by Cambridge University Press

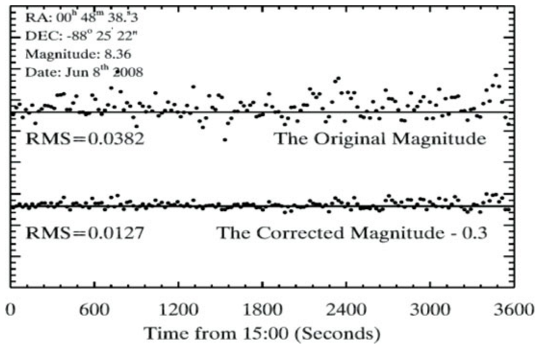

Figure 8. Comparison of the light curves from a series of images obtained under poor photometric conditions. The solid line denotes the mean magnitude of the star in the reference catalog.

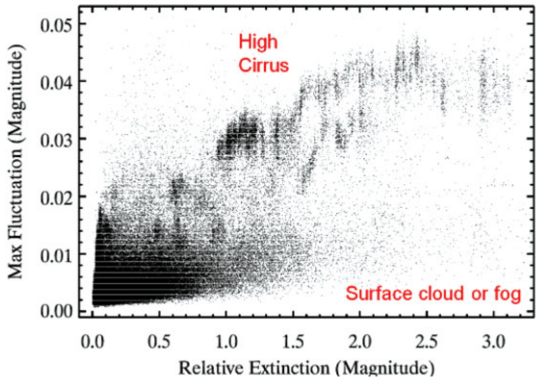

Figure 9. The relationship between the unevenness of extinction and the value of extinction at Dome A.

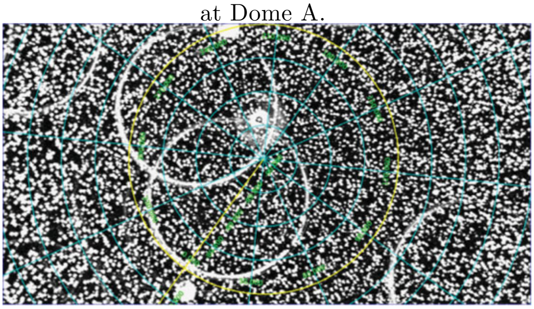

Figure 10. The calibrated position of the object detected in all the images where the objects located in the circles are mostly a "ghost".

planets and detecting possible supernovae, novae, and orphan afterglows of gamma ray bursts from the data. To fit the need of these research works, we need to do further data reduction work to get higher photometric precision, such as inhomogeneous extinction over the field of view, effect of optical "ghosts" and intra-pixel effects, etc.

Passing cirrus cloud usually appears in the Dome A area. Ideally, if the atmospheric extinction is uniform across the FOV or the cloud is absent, we can obtain the true flux of all sources by identical calibrating to standards. Because CSTAR gives about 20 square degrees FOV, we cannot assume the cloud is uniform over all the image fields. A flux calibration with a single value in an image will cause deviations when it is affected by cirrus clouds. Due to the varying extinction over the FOV, a different calibration

https://doi.org/10.1017/S1743921312016936 Published online by Cambridge University Press

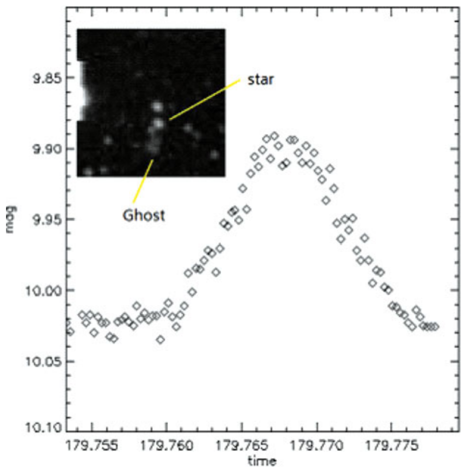

Figure 11. An example of the light curve of a star when a "ghost" passes by, from previous catalog of CSTAR data release.

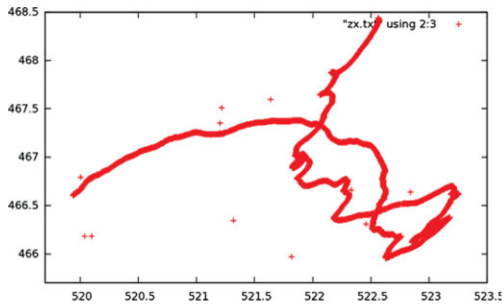

Figure 12. The position of the south celestial pole in the CSTAR field during May 12, 2008.

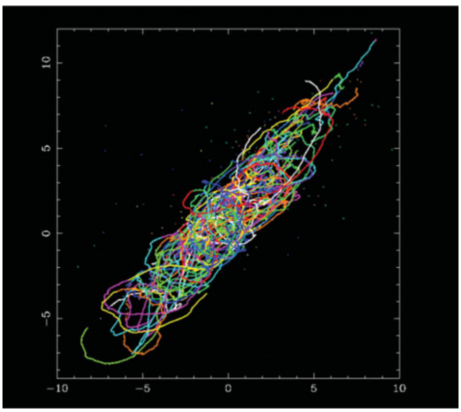

Figure 13. The total south celestial pole positions in all CSTAR images from 2008. We change the color every 24 hours.

is required for each star in the same image. In order to reduce this kind of systematic error, we first made a reference catalog from over ten thousand good photometric stars in the published catalog (Zhou *et al.* 2010a). The reference catalog contains the mean magnitude and mean position of all the stars in the CSTAR FOV. Then, we compared an ensemble of the detected magnitudes of the bright and unsaturated stars in the

https://doi.org/10.1017/S1743921312016936 Published online by Cambridge University Press

published catalog (Zhou *et al.* 2010a) with their magnitudes in the reference catalog. With this distribution of magnitude differences (which yields the cloud structure, as shown in Fig. 7), we updated the published catalog. In the new photometric catalog of 2008, the catalogs of about 20% of images are significantly improved. Fig. 8 shows the effect of correction. And from the relationship between the unevenness of extinction and the value of extinction at Dome A (Fig. 9), the atmospheric extinction at Dome A is considered to be caused by both high cirrus and fog near the snow surface.

In the optical system of CSTAR, many obvious “ghosts” appear in the image. These are mirror images of bright stars after multiple reflections in different optical surfaces. After careful study of the “ghost” behaviour, Meng *et al.* (2012) found that the “ghosts” make daily circular motions in the image. They pass or pass by the positions of many stars in the image. The effect of the ghost changes the measurement magnitude of the stars. The magnitude difference between the “ghosts” and its source objects are about 6 magnitudes and have a fixed symmetry point in the image. Then the influence of the “ghost” on the magnitude of all the real objects can be well calculated.

For further installation and operation of telescopes on the Antarctic plateau, the stability of the ground, floating on thousands of metres of snow and ice, needs to be considered. The observation system of CSTAR is a totally mechanically fixed system. It is firmly fixed on the snow and keeps pointing at the south celestial polar area. So the CSTAR is a unique system for checking ground stability. During the data reduction of the CSTAR, the variation of the telescope pointing is very large. The daily pointing movement can be up to 3 pixels or more than $45''$, as shown in Fig. 12. And the overall movement area during whole observation season of 2008 can be as large as 20 pixels or $5'$, as shown in Fig. 13. Further analysis of this issue will be not only very important for Antarctic astronomical observation but also very important for glaciology studies.

The author thanks the support of National Natural Science Foundation No. 11073032 (PI: Xu Zhou)

References

Bakos, G. Á., Noyes, R. W., Kovács, G., *et al.* 2007, *ApJ*, 656, 552
Boisnard, L. & Auvergne, M. 2006, *ESA Special Publication 1306*, 19
Borucki, W. J., Koch, D., Basri, G., *et al.* 2010, *Science*, 327, 977
Burton, M. G. 2010, *Astronomy & Astrophysics Review*, 18, 417
Crouzet, N., Guillot, T., Agabi, A., *et al.* 2010, *A&A*, 511, A36
Kenyon, S. L., Lawrence, J. S., Ashley, M. C. B., *et al.* 2006, *PASP*, 118, 924
Lawrence, J. S., Ashley, M. C. B., Hengst, S., *et al.* 2009, *Review of Scientific Instruments*, 80, 064501
Meng, Z. Y., *et al.*, 2012, in preparation
Pollacco, D. L.,Skillen, I., Collier Cameron, A., *et al.* 2006, *PASP*, 118, 1407
Saunders, W., Lawrence, J. S., Storey, J. W. V., *et al.* 2009, *PASP*, 121, 976
Strassmeier, K. G., Briguglio, R., Granzer, T., *et al.* 2008, *A&A*, 490, 287
Taylor, M. 1990, *AJ*, 100, 1264
Wang, L., Macri, L. M., Krisciunas, K., *et al.* 2011, *AJ*, 142, 155
Wang, L. Z.,*et al.*, 2012, *AJ*, submitted
Wang S. H., *et al.*, 2012, *PASP*, accepted
Yang, H., Allen, G., Ashley, M. C. B., *et al.* 2009, *PASP*, 121, 174
Yuan, X., Cui, X., Liu, G., *et al.* 2008, *Proc SPIE*, 7012E, 152
Zhou, X., Fan, Z., Jiang, Z., *et al.* 2010, *PASP*, 122, 347
Zhou, X., Wu, Z.-Y., Jiang, Z.-J., *et al.* 2010, *Research in Astronomy and Astrophysics*, 10, 279
Zou, H., Zhou, X., Jiang, Z., *et al.* 2010, *AJ*, 140, 602