

## The Role of NOAO in the Discovery of the Accelerating Universe

Tom Matheson & Chris Smith

The discovery of credible evidence for acceleration in the expansion rate of the Universe is certainly one of the more surprising cosmological results in modern astronomy.

The fact that two independent groups using Type-Ia supernovae as distance indicators—the High-z Supernova Search (High-z SN) team, founded by Brian Schmidt of Australian National University and Nicholas Suntzeff of Cerro Tololo Inter-American Observatory (CTIO), and the Supernova Cosmology Project (SCP) led by Saul Perlmutter of the University of California at Berkeley—both arrived at the same conclusion helped to speed the acceptance of such an unexpected result.

Subsequent data from ground-based and space-based programs, including studies using tools other than SNe, have confirmed the initial results, although the nature of the “dark energy” that is apparently driving this acceleration is still uncertain. The first reports, though, were the product of essentially ground-based programs that relied heavily on the resources of the National Optical Astronomy Observatory.

At the time when the two groups were developing their programs, new observations of Type-Ia SNe showed that they were not homogeneous standard candles. Early CCD observations of SN 1986G obtained at CTIO showed it to be unusual.

In 1991, two SNe (the overluminous SN 1991T and the underluminous SN 1991bg) provided unquestionable evidence that SNe Ia are heterogeneous, with a spread of 2.5 magnitudes at peak brightness.

Fortunately, the Calan/Tololo SN survey had begun in 1989. This search was led by Mario Hamuy, Mark Phillips, Nicholas Suntzeff (all CTIO astronomers at the time), and Jose Maza (Universidad de Chile). They used the CTIO Curtis Schmidt camera to search for SNe, timing the observations to catch SNe soon after explosion. Most of the photometry of the newly discovered SNe was obtained with the CTIO 0.9-meter telescope, while the CTIO 1.5-meter and Blanco 4-meter telescopes provided most of the spectroscopy.

Analysis of this well-observed and well-calibrated SNe sample showed that the peak brightness of a Type-Ia SN was correlated with the light-curve shape. Using the light curve, one could transform a relatively diverse set of Type-Ia SNe into “calibratable” standard candles. Without this calibration, neither team could have obtained luminosity distances to high-redshift Type-Ia SNe with the precision necessary to detect the subtle effect introduced by the acceleration of the expansion. These SNe also provided the low-redshift anchor for the cosmology derived from the high-redshift SNe. The Calan/Tololo survey was essential to the success of each cosmological program.

The techniques for finding high-redshift SNe began with a Danish group using the 1.5-meter telescope at ESO. They adopted a timing scheme similar to that used by the Calan/Tololo survey. Expanding on this, the SCP started using the Kitt Peak Mayall 4-meter and 2.1-meter telescopes for searches and photometry. With these facilities, they refined the strategy of observing blank fields to catch high-redshift SNe early in their development. These early runs often shared fields with other programs to extend the utility of the data, a practice continued with many later SNe searches.

In order to find large numbers of SNe at high redshift, both teams employed the wide-field imaging capability of the Blanco 4-meter telescope at CTIO. Initially, they used the prime-focus CCD camera, switching to the Big Throughput Camera when it became available. Previously obtained template images were subtracted from frames during SNe searches. Promising new objects could then be observed spectroscopically to securely identify the new object as a Type-Ia SN. Multiple epochs of photometry (often with the Blanco 4-meter) produced light curves that could be anchored using the calibration

provided by the Calan/Tololo sample.

The WIYN 3.5-meter telescope at Kitt Peak was used by the High-z SN team and the SCP to observe many of the high-redshift SNe found by the Blanco 4-meter telescope. One of the reasons that WIYN was particularly useful was

that it was operating with a queue schedule at that time. For transient objects such as SNe, the ability to obtain observations on demand is a tremendous resource. Both teams explicitly acknowledged the importance of the WIYN queue observers to their projects.

NOAO facilities continue to play an important role in studies of dark energy. The Blanco 4-meter is the host of the NOAO Survey project Equation of State: SupErNovae trace Cosmic Expansion (ESSENCE), which is searching for more high-redshift Type-Ia SNe in order to constrain the equation-of-state parameter of dark energy (see [www.ctio.noao.edu/essence](http://www.ctio.noao.edu/essence)). NOAO supports both ESSENCE and the Canada-France-Hawaii Telescope SN Legacy Survey in their use of the Gemini Observatory to obtain spectra of high-redshift SNe.

The Blanco Cosmology Survey ([www.cosmology.uiuc.edu/BCS](http://www.cosmology.uiuc.edu/BCS)) will also attempt to constrain dark energy through observations of clusters of galaxies. In the near future, the Dark Energy Survey ([www.darkenergysurvey.org](http://www.darkenergysurvey.org)) will build the 500-megapixel Dark Energy Camera for the Blanco, dramatically expanding survey capabilities for NOAO and its user community, and enhancing the observatory’s historic place in the quest to understand the mystery of the accelerating universe.



# Latitude Distribution of Polar Magnetic Flux

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The magnetically unipolar-dominated polar caps are among the most prominent solar features throughout the activity cycle of the Sun, particularly at solar minimum. The magnetic fields, concentrated in small elements due to solar convection, expand with height and spread out to fill most of the heliosphere, in addition to creating numerous fine coronal structures. These regions also harbor the streaming fast solar wind, and the processes responsible for the plasma heating and acceleration near the Sun.

These regions are among the most challenging to interpret. Despite the great importance of the solar polar areas for numerous solar and astrophysical phenomena (e.g., coronal heating, solar wind acceleration, cosmic ray propagation, etc.), the polar caps are not sufficiently studied because of observational and modeling difficulties. This is due mainly to the weakness of the polar magnetic fields and the unfavorable solar geometry close to the limb, which makes measurement of the polar regions difficult from the ecliptic plane. Instrumental limitations in matters of sensitivity and accuracy are another major handicap. In order to get significant measurements of the polar magnetic field, instruments with high polarimetric sensitivity and spatial resolution are needed.

Chromospheric line-of-sight (LOS) magnetograms from the SOLIS Vector Spectromagnetograph (VSM) are utilized to study the latitudinal distribution of the magnetic flux in the polar regions. These Ca II 854.2 nm magnetograms have an advantage with respect to photospheric magnetograms close to the solar limb because of the spreading canopy structure of the magnetic field in the chromosphere, which provides a better signal in the LOS field close to the limb (see figure 1).

Magnetic flux elements are identified and located using simple closed-structure recognition methods. An average location in terms of latitude is determined for every selected feature and a histogram is computed for their distribution as a function of latitude. The obtained histograms are normalized by the surface area distribution corresponding to each latitude bin to remove any bias due to the observed area of the polar cap. The solar geometry in terms of the polar axis tilt ( $B_0$  angle) is taken into account. This procedure was repeated for every magnetogram

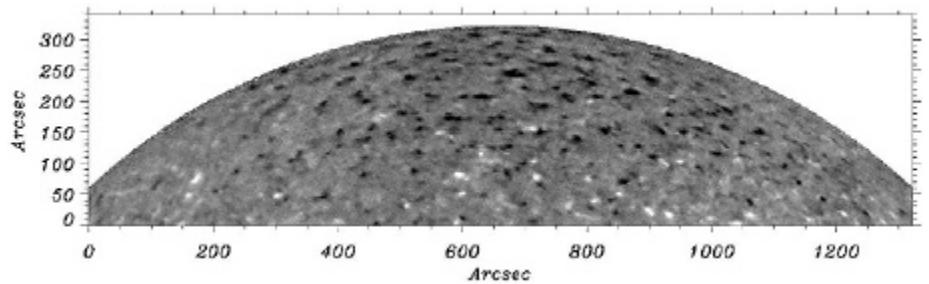


Figure 1. Typical chromospheric (Ca II 854.2 nm) line-of-sight magnetogram from the SOLIS/VSM recorded on 22 October 2006. Flux elements are easily identified due to the good visibility everywhere on the solar disk.

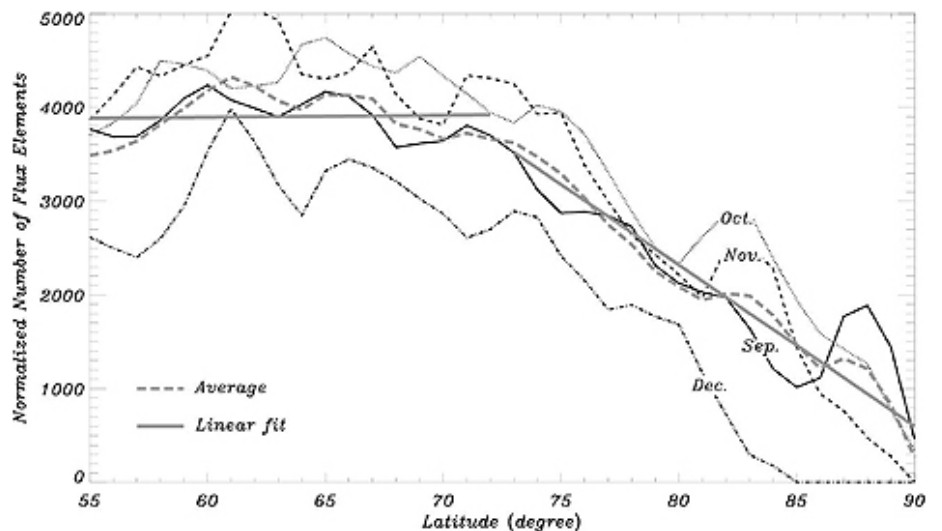


Figure 2. Monthly averaged histograms of the magnetic flux distribution as a function of latitude for the north polar cap. The grey dashed curve is the average of the monthly averages. The straight lines are linear fits for portions of the grey dashed curve for latitudes ranging from 55°–73° and 74°–90°.

recorded in the time interval September–December 2006. The north solar pole is well seen during this period. Daily distribution histograms are noisy, and therefore are averaged for every month and for the whole period considered here.

We find that the density distribution of the magnetic flux elements within the northern polar cap observed during September–December 2006 has a strong dependence on latitude (see figure 2). The flux distribution normalized to the surface of the polar cap is relatively flat up to latitudes of about 75°–80°, where it drops significantly up to the solar pole. This result is confirmed for the whole period of observations considered. There is also a relative difference in the distributions of flux elements

of different sizes. Large flux elements show a preferential high density at low latitudes.

We believe that the mechanisms responsible for the flux transport from low latitudes toward the solar poles are less efficient close to the poles. This means that the meridional circulation responsible for the flux transport slows before reaching the poles. Such a result would have a significant impact on the theories and models dealing with flux transport. These results also put important constraints on solar phenomena that are inaccurately (if at all) determined by other means, such as helioseismic studies that become inefficient at high latitudes. More details will be published in a paper in press with the *Astrophysical Journal* (vol. 668, October 2007).

# Cosmology Revealed by WIYN Imaging

Steve Howell

WIYN telescope observations aimed at surveying galaxy clusters for lensing events have struck gold thanks to high-resolution imaging. Using Mini-Mosaic and the Orthogonal Parallel Transfer Imaging Camera (OPTIC), the two workhorse imagers at the WIYN 3.5-meter telescope on Kitt Peak, Joe Hennawi (University of California at Berkeley) and collaborators have found new, exciting examples of lensed systems (see *astro-ph/0610061*).

Hennawi et al. ask the question, “Does the currently favored  $\Lambda$ CDM cosmological model explain the detailed distribution of dark matter in galaxy clusters?” This group is using strong gravitational lensing by clusters of galaxies as a powerful test of this model. They are probing the largest collapsed structures of dark matter in the Universe. The multiply imaged background galaxies and highly distorted giant arcs in well-known clusters like Abell 1689 and CL0024+1654 can be used to construct detailed models of the dark matter gravitational potential. Beside providing cosmological constraints, lensing clusters are natural gravitational telescopes, and their high magnification enables the study of the faintest, most distant known galaxies ( $z \sim 6-9$ ), which would otherwise be unobservable.

Astrophysicists have been studying the same handful of strong-lensing clusters for nearly a decade, and their interpretation and

understanding have been limited by poor statistics. The Hennawi survey aims to dramatically increase the number of known cluster lenses by combining the  $\geq 2 \text{ Gpc}^3$  cosmological volume of the Sloan Digital Sky Survey (SDSS) with the exceptional imaging capability provided by the WIYN telescope.

Clusters of galaxies in range  $z \leq 0.6$  can be efficiently identified in the SDSS multicolor imaging, which covers  $8,000 \text{ deg}^2$ ; however, the SDSS imaging is too shallow and the image quality too poor to detect the much fainter gravitationally lensed background sources. The strategy of the Hennawi survey is to obtain deep high-resolution WIYN images of the most massive clusters in the SDSS volume. Thus far, the group has imaged  $\sim 160$  clusters in sub-arc conditions and discovered  $\sim 30$  new lensing clusters, nearly doubling the total number of such systems known!

The two new systems shown in figure 1 and 2 (and several others discovered in this survey) will likely become ‘poster-child’ lenses similar to Abell 1689 and CL0024+1654. By conducting the largest survey for cluster lensing to date, this WIYN high-resolution imaging survey will help transform strong lensing by galaxy clusters from the study of a handful of rare systems into a powerful statistical probe of the formation of structure in the Universe.

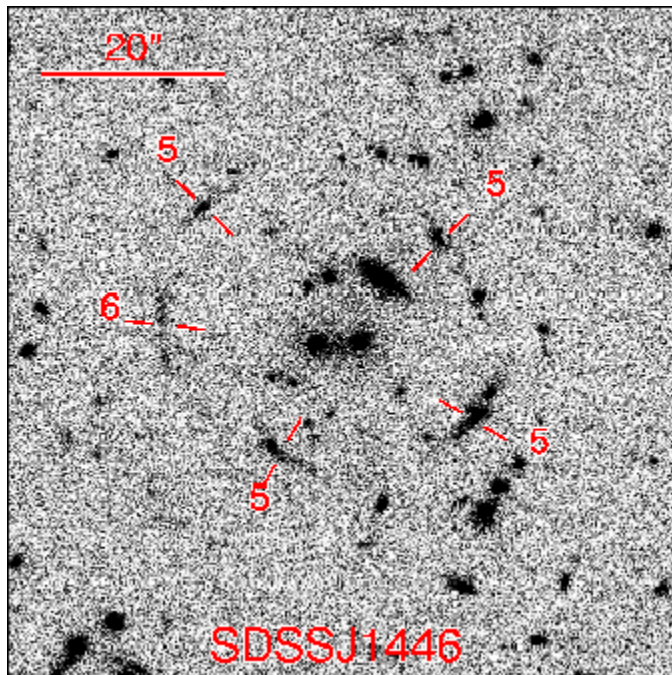


Figure 1. WIYN OPTIC g-band image of SDSSJ1446+3032. This cluster at  $z=0.47$  is one of the most dramatic examples of strong gravitational lensing ever discovered. Because of the excellent image quality (FWHM=0.63 arcsec), it is easy to see five extended blue high-surface-brightness arcs oriented in an ellipse about the cluster center.

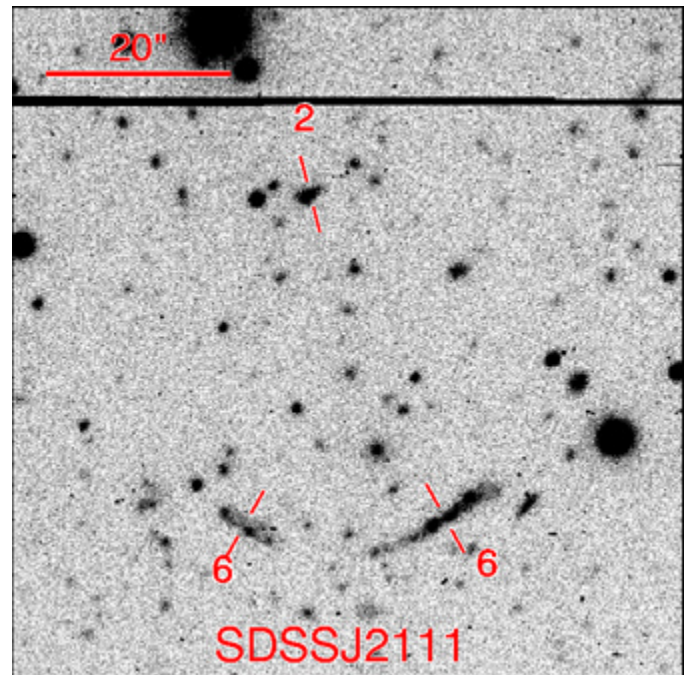


Figure 2. WIYN Mini-Mo image (FWHM=0.74 arcsec) of another lensing cluster, SDSSJ2111-0115 at  $z=0.68$ . Two very-high-surface-brightness arcs are apparent south of the cluster center, and a possible counter arc is flagged about 40 arcsec to the north.