



High-Resolution Near-Infrared Spectroscopy of FU Ori Objects

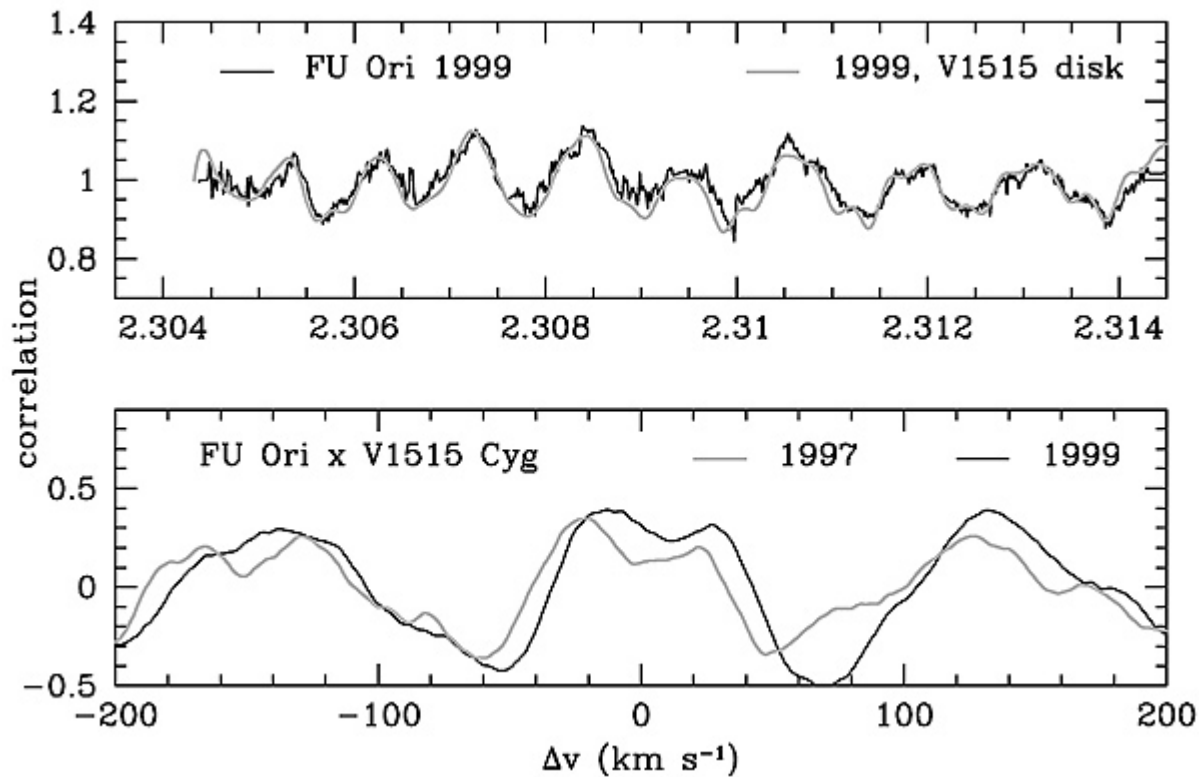
Lee Hartmann (Harvard-Smithsonian, CfA)

FU Orionis objects are a remarkable class of eruptive pre-main sequence systems whose unusual properties may arise from the presence of a rapidly accreting ($10^{-4} M_{\odot}/\text{yr}$) circumstellar disk (Hartmann & Kenyon 1996). The accretion disk model explains the broad spectral energy distributions of these objects, as well as why near-infrared spectra of these objects show later spectral types and slower rotational velocities than spectra taken at optical wavelengths: the longer wavelength spectra probe the outer, cooler, more slowly rotating regions of the disk. Finally, the disk model predicts “doubled” line profiles, which are often (though not always) detected. A significant amount of mass can be accreted during an FU Orionis outburst: FU Ori itself has been in a high state since the 1930s, and therefore we infer that it has accreted approximately $0.01 M_{\odot}$, or

approximately a minimum-mass solar nebula, during that time. More generally, rapid disk accretion in FU Orionis outbursts may be a part of the evolutionary history of all low-mass stars. As a result, there is considerable interest in verifying the disk paradigm for FU Ori objects.

Recently Herbig et al. (2003) raised questions about the disk model based on optical and near-infrared spectra of FU Ori and a similar system, V1057 Cyg. To address some of these questions, we analyzed (Hartmann, Hinkle, & Calvet 2004) high-resolution spectra in the region of the first-overtone CO bands obtained with the Phoenix spectrometer (Hinkle et al. 1998, 2003) on the Kitt Peak 2.1-m telescope and the Gemini South 8-m telescope.

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Upper panel: Comparison of Phoenix spectrum of FU Ori (black line) with a synthetic disk spectrum (gray line). Lower panel: Cross-correlations of FU Ori spectra with a narrow-lined template spectrum (V1515 Cyg). The broad cross-correlation is double-peaked, as predicted for a rapidly-rotating disk; the same structure is seen in both epochs, with a possible radial velocity shift.



High-Resolution Near-Infrared Spectroscopy continued

Herbig et al. had called attention to the appearance of narrow optical emission lines of low-excitation species in V1057 Cyg starting in 1997. They interpreted these emission features as resulting from a chromosphere that, in a weaker state, produced the line doubling seen at earlier epochs. We found that the 1997 Phoenix spectrum of V1057 Cyg showed very strong “shell” absorption in the first-overtone CO lines, blueshifted by about 50 km/s from the system velocity. The physical properties of this shell are uncertain, but we estimated an excitation temperature of $\sim 600\text{K}$ and a total column density possibly as large as 10^{23} cm^{-2} . We suggested that V1057 Cyg ejected cold, dense, massive shells, which at least qualitatively account for the CO absorption, the optical decline (probably due to dust obscuration; Ibrahimov 1999), and the low-temperature optical lines seen in both emission and absorption by Herbig et al.

We also analyzed the CO line profiles of FU Ori in some detail. The figure shows Phoenix spectra of FU Ori compared with a predicted disk spectrum calculated by convolving the rotational line profile with the Phoenix spectrum of V1515 Cyg, a slowly-rotating (pole-on) FU Ori object. The comparison is reasonably good, suggesting that the line broadening predicted for a rotating disk is consistent with the observations. This can be tested without

using a model by cross-correlating the V1515 Cyg spectra with FU Ori; the resulting cross-correlation peaks reflect the average line profile in the rapidly rotating object. As shown in the bottom panel of the figure, the cross-correlations show a double-peaked structure, as expected for a rotating disk, and this structure is repeatable between the 1997 and 1999 spectra. Moreover, the rotational velocity broadening in the near-infrared remains considerably smaller than that observed in the optical, consistent with the predictions of a differentially rotating disk.

These observations indicate the potential of continued optical and near-infrared monitoring at high spectral resolution for increasing our understanding of pre-main sequence disk accretion. It is likely that mass ejection is continuously variable, with occasional large eruptions, and multiwavelength monitoring could yield new insights into the physics of the outflows. Our detailed models suggest the need for sonic or even slightly supersonic turbulent broadening in the disk atmosphere, which may be a necessary by-product of the magnetorotational instability (Miller & Stone 2000). It is not clear whether the small velocity shift seen between the two epochs in the figure is significant, but it might be an indication of a companion object (Clarke & Armitage 2003). The FU Ori objects have not yet yielded all of their secrets.

Special Session on the NOAO Deep Wide-Field Survey at the June AAS Meeting

Arjun Dey (NOAO)

The NOAO Deep Wide-Field Survey (NDWFS; see cover image) was recently the focus of a well-attended Topical Session at the June 2004 AAS meeting in Denver. The survey (PIs Arjun Dey and Buell Jannuzi) consists of two 9 square degree fields, one in Boötes and one in Cetus, which have been mapped to approximately $0.1\ \mu\text{Jy}$ depth at optical wavelengths and approximately $10\ \mu\text{Jy}$ depth in the near-infrared. The two survey fields provide the unprecedented ability to investigate the clustering and evolution of galaxies over large scales

and over a wide range in redshift. As a result of this large ground-based campaign, successfully mounted by NOAO staff members, the Boötes field of the NDWFS is now being studied by a large number of observing programs, spanning X-ray to radio wavelengths and using facilities in space and on the ground.

As vivified by the session talks (archived at www.noao.edu/noao/noaodeep/AAS2004/), the Boötes field is fast becoming one of the best-studied regions of the sky: it has

now been mapped in its entirety at X-ray wavelengths by Chandra (AAS presentation by Steve Murray, CfA), at UV wavelengths by GALEX (presentation by Charles Hoopes, Johns Hopkins University), at 3.6, 4.5, 5.8, 8, 24, 70, and $160\ \mu\text{m}$ by Spitzer (presentations by Tom Soifer, Caltech; and Peter Eisenhardt, JPL; see following article), and at radio wavelengths by the VLA at 20 and 90 cm and Westerbork at 20 cm (presentations by Jim Higdun, Cornell University; and Steve Croft, LLNL).

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NOAO Deep Wide-Field Survey at AAS continued

Additional surveys carried out with NOAO facilities have targeted smaller regions within the Boötes field. One of the NOAO Survey programs, the FLAMINGOS Extragalactic Survey (FLAMEX; presentation by Anthony Gonzalez, University of Florida), which was completed this spring, has carried out deep J K_s imaging over a ~ 5 square degree region. Narrowband imaging of a portion of the Boötes field has been carried out by the Large Area Lyman Alpha (LALA) survey for line-emitting galaxies at $z=4.5$, 5.7, and 6.5 (presentation by James Rhoads, STScI).

At the AAS session, Steve Murray (CfA) also presented early results from the AGES survey (PIs Chris Kochanek, Ohio State University; and Daniel Eisenstein, University of Arizona) which is obtaining MMT/Hectospec spectra for a complete, magnitude-limited sample of galaxies and AGN in the Boötes. The wide coverage and depth of all of these multiwavelength surveys render themselves invaluable to detailed studies of galaxy and AGN evolution. The NDWFS is also becoming a focus of future space missions: Daniel Stern (JPL) described plans for a future hard-X-ray survey of the field by the MIDEX satellite NuSTAR. The depths of all of these current and future surveys are summarized in figure 1.

The presentations at the session focused on a wide range of topics related to galaxy evolution, ranging from studies of AGN evolution at $z < 1$ (Kate Brand, NOAO) to searches for clusters at $z > 1$ (Peter Eisenhardt, JPL; and Anthony Gonzalez, University of Florida; see figure 2); from extended X-ray emission from nearby star-forming galaxies (Casey Watson, Ohio State University) to Ly α emission from star-forming galaxies at $z \sim 6$ (James Rhoads, STScI;

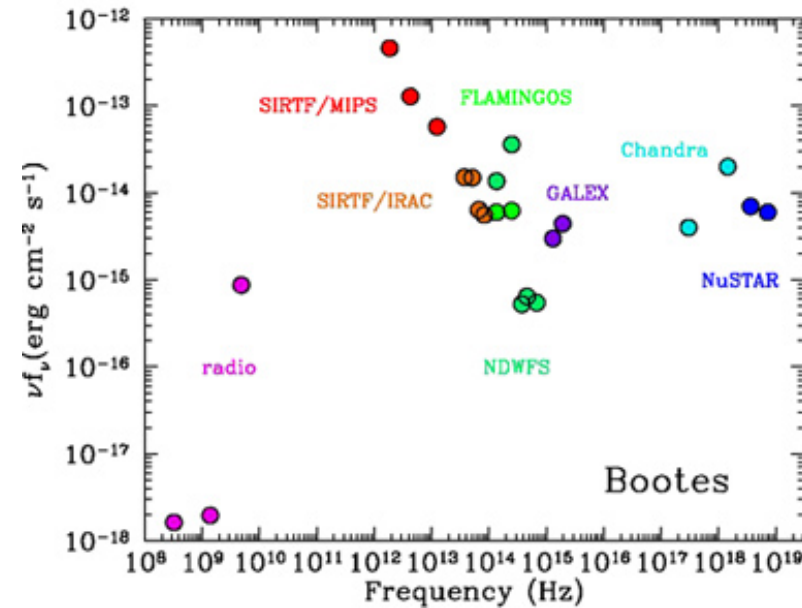


Figure 1: Depths of current and future studies of the Boötes field as a function of wavelength (figure courtesy of Daniel Stern, JPL).

see the June 2004 *Newsletter*); and from optically invisible radio sources (Jim Higdon, Cornell University; and Steve Croft, LLNL) to optically invisible 24- μ m sources (Tom Soifer, Caltech).

Steve Dawson (University of California at Berkeley) presented results from the LALA survey for the redshift range $z \sim 4.5$. This survey has yielded the largest sample (~ 80) of narrow-lined emitters thus far at this redshift. About a quarter of the sample shows large Ly α equivalent widths, suggesting that these galaxies are young, star-forming systems. However, the stacked spectra show no evidence for HeII, suggesting that the gas in these galaxies is unlikely to be primordial. The lack of detectable CIV or X-ray emission from this population suggests that the AGN fraction in these galaxies is small (Junxian Wang, Hefei, China).

Michael Brown (NOAO & Princeton) presented studies of the spatial clustering of the red galaxy population (see the March 2003 *Newsletter*) and extremely red objects. Richard Green (NOAO) presented recent results on a survey of K -band selected QSOs.

The diversity and number of presentations at the meeting illustrated the growing community interest and involvement in the NDWFS. We invite our readers to browse the meeting presentations at www.noao.edu/noao/noaodeep/AAS2004/.

One square degree of the ground-based optical survey data are currently available through the NOAO Science Archive (archive.noao.edu/nsa/). All of the NDWFS optical and near-IR data in the Boötes field will be available through this archive on 22 October 2004.

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NOAO Deep Wide-Field Survey at AAS continued

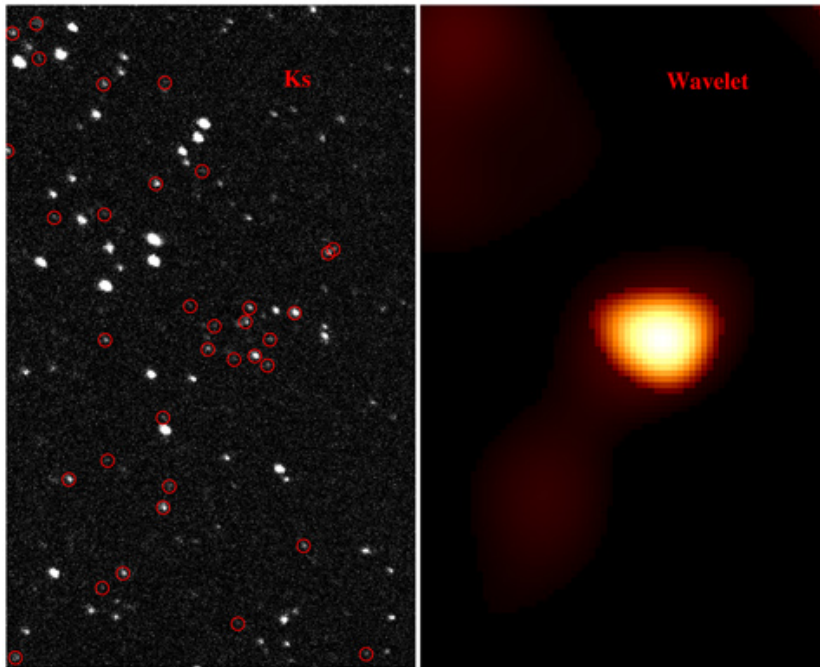


Figure 2: The first spectroscopically confirmed galaxy cluster from the FLAMINGOS Extragalactic Survey, an NOAO Survey Program that uses FLAMINGOS on the KPNO 2.1-m. The left and center panels show the K_s - and J-band imaging with red circles overlaid to mark objects with $J-K_s > 1.75$. As a preliminary means of identifying clusters, galaxies redder than this threshold (which should lie at $z > \sim 1$) are used as input for a wavelet analysis that identifies structures on scales of ~ 30 – 100 arcsec (right panel). The galaxy cluster shown is spectroscopically confirmed with Keck to lie at $z = 1.05$ (figure courtesy of Anthony Gonzalez and Richard Elston, University of Florida, and the FLAMINGOS Extragalactic Survey team).

Surveying the NOAO Deep Wide-Field Survey with IRAC

Peter Eisenhardt, Daniel Stern & Mark Brodwin (Jet Propulsion Laboratory)

The millionfold lower background seen at infrared (IR) wavelengths in space means that even brief exposures with a modest aperture telescope like the Spitzer Space Telescope probe vastly larger volumes than are possible from the ground. For objects distributed uniformly in Euclidean space, the number of sources detected is maximized by observing a given field only long enough to become background limited, and to reduce repositioning overheads to one-third of the observing time. Such considerations motivated a survey with the Spitzer Infrared Array Camera (IRAC) of the Boötes region of the NOAO Deep Wide-Field Survey

(NDWFS; see previous article). Much as the Hubble and Chandra Deep Fields have become the fields of choice for ultradeep pencil-beam surveys across the electromagnetic spectrum, Boötes has become the wide-area, deep survey field of choice. The resulting IRAC shallow survey (Eisenhardt et al.) covers 8.5 square degrees of the Boötes field with 90-second exposures per position. The survey detects approximately 370,000, 280,000, 38,000, and 34,000 sources brighter than the 5σ limits of 6.4, 8.8, 51, and 50 μJy at 3.6, 4.5, 5.8, and 8 μm respectively.

A major scientific driver for the IRAC shallow survey is the detection of galaxy

clusters at $z > 1$ via the redshifted 1.6- μm peak in galaxy spectral energy distributions. Extending the evolution observed in the K-band in clusters to $z \sim 1$, we expect to detect cluster galaxies fainter than L' at $z = 2$ at 3.6 and 4.5 μm . The survey should also be an extremely powerful tool for studying the evolution of large-scale structure out to $z \sim 2$. Additionally, the shallow survey team plans to address many other astrophysical objectives using these data sets, ranging from identifications and size estimates for high ecliptic latitude asteroids from 8 μm thermal emission, to identification of T-type and cooler field brown dwarfs based on methane



Surveying the NOAO Deep Wide-Field Survey with IRAC continued

absorption that produces extremely red 3.6 to 4.5 μm colors, to studying and identifying obscured AGN across cosmic history, to foreground subtraction for the detection of fluctuations in the 1 to 3 μm cosmic background due to Ly α emission from Population-III objects at $z \sim 15$ (e.g., Cooray et al. 2004).

Finally, the IRAC shallow survey, by virtue of pushing several orders of magnitude into area-depth discovery space, is expected to identify new, rare objects. As an example, we have thus far identified a handful of sources with extreme optical-to-mid-IR colors in a 1.2 square degree region of the NDWFS (see figures 1 and 2). The 8 μm to 0.8 μm flux ratio of the objects is >500 , which corresponds to a spectral index of >2.7 . These unusual optical-to-mid-IR colors could be caused by moderate-redshift, extremely-dusty starbursts where PAH emission augments the mid-IR emission. Extremely dusty, moderate-redshift AGN could also produce such extreme colors. Finally, an intriguing, but less likely possibility is a population of quasars at $z > 6$ for which the Ly α forest suppresses light below 1 μm . Comparison of template spectral energy distributions with the observed colors show that none of these scenarios are completely satisfying; follow-up observations with Spitzer's Infrared Spectrograph are likely to reveal which of these possibilities is correct, or whether these objects represent a new phenomenon. Given the large volume probed by the IRAC shallow survey, many more objects with unusual colors may await discovery.

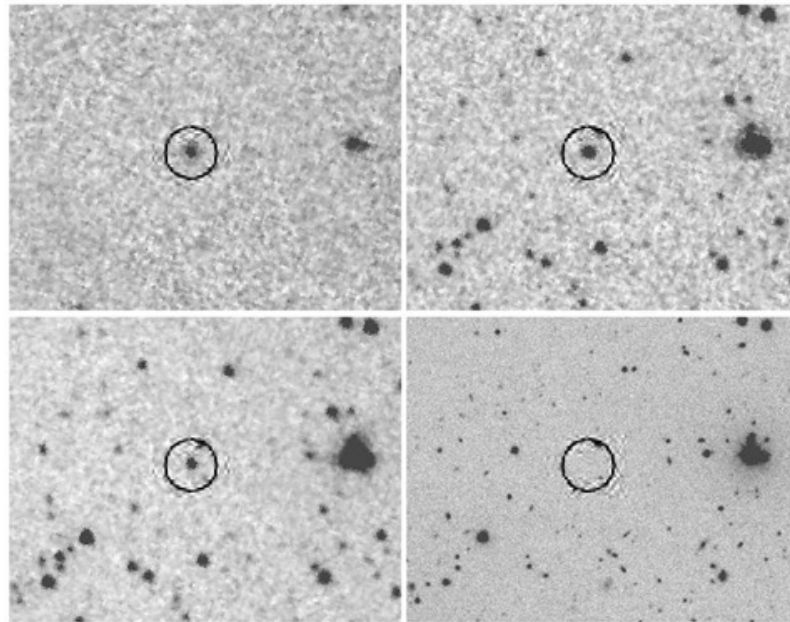


Figure 1. One of the extreme 8 μm to I flux ratio objects detected in the IRAC shallow survey, IRAC J142939.1+353557. Images are approximately 1.5 arcmin on a side. Clockwise from top left, images are through 8 μm , 4.5 μm , I-band, and 3.6 μm filters. This source is bright in the mid-infrared, with an 8 μm flux >0.2 mJy. At optical wavelengths, the source has $I_{AB} > 24.5$, making followup ground-based spectroscopy challenging, if not impossible.

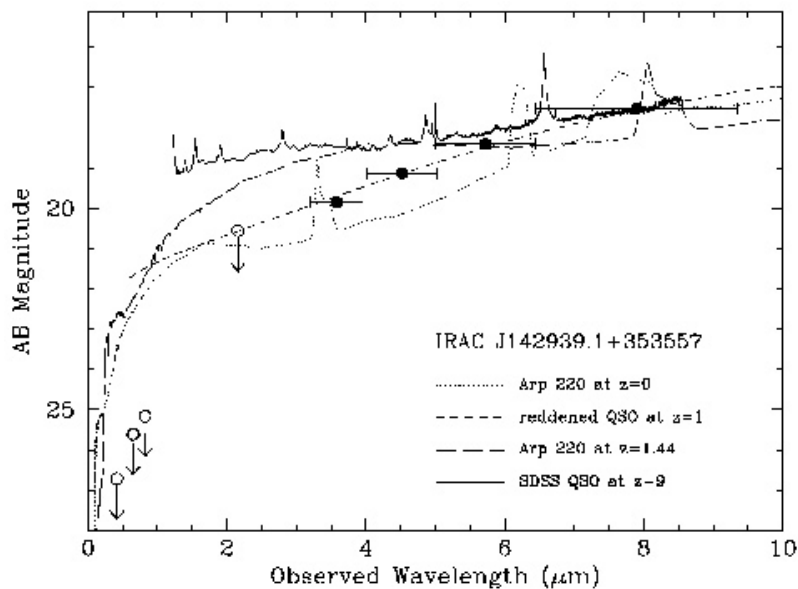


Figure 2. Spectral energy distribution of IRAC J142939.1+353557 compared with several models that have been proposed to explain the unusual colors.



Observational Evidence for Magnetic Flux Submergence

Alexei A. Pevtsov (NSO)

It is widely believed that the magnetic field on the Sun is generated by a dynamo operating at the base of the convection zone, although recent studies suggest that there may be a second dynamo operating at or near the visible solar surface, the photosphere. In 1984, Eugene Parker concluded that only a small fraction of magnetic flux threading the solar surface can escape. He also pointed out an inconsistency between the upper limit of magnetic flux stored at the base of the convection zone and the rate of flux emergence in a long-lived complex of activity. To resolve this “dynamo dilemma,” Parker suggested that magnetic flux retracts below the surface and is recycled several times. So far, however, this flux submergence has proven to be illusive.

Magnetic flux concentrations in the photosphere often disappear via flux cancellation when opposite poles collide with each other and vanish. Figure 1 (upper panel) shows the expected topology of the magnetic field at a flux cancellation site. Two independent magnetic elements with opposite polarity approach each other and reconnect. The reconnection forms two loop-like structures: concave-up and concave-down. The magnetic tension would try to “shorten” newly formed “loops,” and thus, at the place of maximum curvature (apex/valley), one loop would show rising motions, and the other would show descending motions. The observer would see only one loop crossing the photosphere whenever the reconnection took place below or above the photosphere.

Using high-resolution vector magnetograms of active region NOAA 10043, observed on 26 July 2002 with the Advanced Stokes Polarimeter and low-order adaptive optics system at the Dunn Solar Telescope at Sacramento Peak, we studied the magnetic field topology and line-of-sight velocities at two flux cancellation sites. Figure 1 (lower panel) shows the magnetic field (B) and line-of-sight velocities (V) associated with one canceling feature. Near the cancellation site, the longitudinal magnetic field (B_{\parallel}) vanishes (grayscale), but the transverse field (B_{\perp}) reaches its maximum (white areas). This implies that the magnetic field is mostly horizontal there, in agreement with Figure 1b and c scenarios. However, the velocity map (V from I) shows significant downflows (white half-tone areas) where the magnetic field is horizontal, suggesting that the magnetic field is moving downward. Figure 2 shows Stokes profiles at the flux cancellation site that support our description of plasma motions and the magnetic field topology. These rare observations provide the first observational evidence for the submergence of magnetic flux on the Sun.

This work was done in collaboration with Jongchul Chae (Seoul National University and Big Bear Solar Observatory), and Yong-Jae Moon (Korea Astronomy Observatory and Big Bear Solar Observatory).

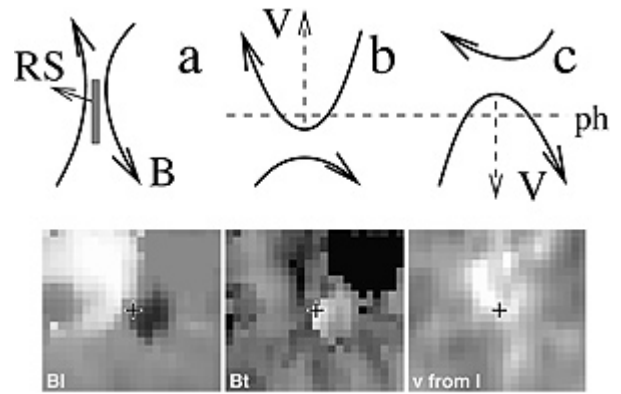


Figure 1. Upper panel: Schematic representation of the magnetic topology at a flux cancellation (reconnection) site (RS) prior to reconnection (a) and after reconnection below (b) and above (c) the photosphere (ph, horizontal dashed line). Solid lines with arrows represent the magnetic field B, and vertical dashed arrows show the direction of motion of newly formed loops. Lower panel: Observations of a flux cancellation site; longitudinal field B_{\parallel} (white/black corresponds to positive/negative polarity), transverse field B_{\perp} , and Doppler velocity V (white half-tone corresponds to downward motions). The flux cancellation site is marked by a “+”.

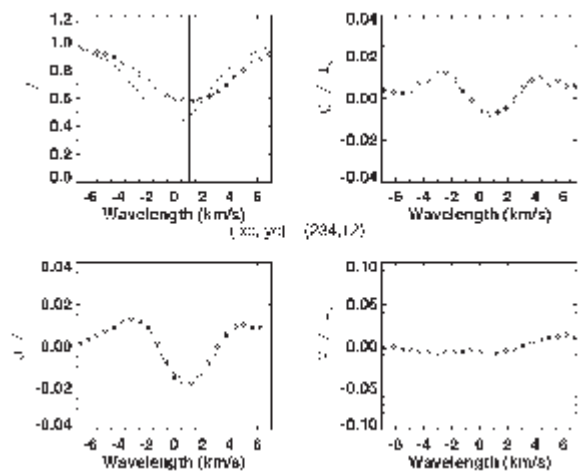


Figure 2. Stokes profiles at the flux cancellation site shown in figure 1. The wavelengths for all profiles are expressed in units of velocity relative to the nearby quiet Sun. Negative velocity corresponds to blueshift, or upward (with respect to image plane) motions. The dotted curve in the top left panel shows the Stokes I profile from the quiet Sun area. The vertical solid line represents the center of the Stokes profile.