The Evershed Flow: From the Chromosphere to the Photosphere

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It has been known for almost a century that sunspots are the visible manifestations of strong concentrations of magnetic field on the solar surface. Yet despite a hundred years of intense study, many physical details of sunspot structure and dynamics remain uncertain. Among the unexplained features is the characteristic outflow that occurs at photospheric levels in sunspot penumbras discovered by Evershed in 1909 at almost the same time the magnetic nature of spots was determined. In spots observed toward the solar limb, this predominantly horizontal flow manifests itself very clearly in the shifts of spectral lines toward the blue in the center-side penumbra, and to the red on the limb side, as illustrated in the Dopplergram taken in the magnetically insensitive 709.04 nm line of Fe I (figure 1).

Figure 1. Dopplergram derived from the line-wing intensity of the Fe I 709.04 nm line. Positive velocities (dark) point away from the observer and correspond to blueshifts, while negative velocities (bright) point toward the observer and correspond to blueshifts. The arrow points toward disk center. Contour lines mark the visible umbra and penumbral boundaries. The field of view is 81 arcsecs.

When higher layers of the penumbral atmosphere are probed with stronger spectral lines, the visible picture changes considerably. This is illustrated by the image in the Ca II 854.21 nm line, which samples chromospheric layers (figure 2). Higher up, the atmosphere is dominated by dark fibrils — loop-like structures that are more or less aligned radially and extend far beyond the visible penumbra. They are also clearly visible in the Hα line, where the structure they outline is named the superpenumbra. The fibrils carry an inward flow toward the umbra, called the inverse Evershed flow, which is almost certainly associated with the larger scale organization of the magnetic field around sunspots.

Figure 2. Line-core intensity of the Ca II 854.21 nm line.

As in the case of the photospheric Evershed flow, the driving force of the inverse flow remains unclear. It has been suggested that the inflow is a siphon flow, driven by the difference in gas pressure between the two footpoints. In this case, the flow direction is from lower magnetic field strength to higher field strength. This is plausible if the fibrils arch into the chromosphere from the high field strength umbra to connect to weaker field concentrations such as pores, or magnetic network elements, outside the spot.

The Interferometric Bidimensional Spectrometer (IBIS), a new instrument at the Dunn Solar Telescope (DST) on Sacramento Peak, now allows monitoring of the chromospheric layers above sunspots through the Ca II 854.21 and H I Hα lines at high spatial and temporal resolution, optimally using the telescope’s adaptive optics (AO) system.

The Dopplergram in the Ca II 854.21 nm line shown in figure 3 is an example of the high quality data that are achievable with this setup. It is part of a two-hour observation obtained with IBIS in summer 2006 during excellent seeing conditions. Although we lack magnetic field information for the present observations, polarimetric capabilities have recently been added to the instrument to aid future investigations on the bewildering nature of chromospheric penumbra. Present observations provide strong evidence for a significant vertical component of the chromospheric inflow. While the flow seems to be almost horizontal in the superpenumbra, it becomes increasingly vertical towards the penumbra. In the chromospheric Dopplergram (figure 3), this configuration, in combination with the viewing angle, causes the flow pattern to be visible beyond the photospheric signature of the penumbra on the limb side, while on the center-side penumbra it is well observed within the visible penumbra.

Figure 3. Dopplergram derived from the line-core intensity of the Ca II 854.21 nm line.

The origin of these counter flows is unresolved, as are many other questions related to the chromospheric penumbra. What is the connection between the photospheric and chromospheric penumbral flow systems? Where are the photospheric counterparts of the chromospheric down flows? Where do the loops have their footpoints? Are the chromospheric flows stationary or periodic? What is the magnetic field structure of the chromospheric loops, and how does it connect to the observed flows in both the chromosphere and the photosphere?

Determination of the physical forces that drive both the regular and the inverse Evershed flow is essential to our understanding of the formation, evolution, and decay of sunspots, and highly relevant to the prediction of active region evolution and its influence on space weather.
High Spectral Resolution in the Mid-IR with TEXES on Gemini

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With the arrival in 2006 of the Texas Echelon-Cross-Echelle Spectrograph (TEXES) at Gemini North, a new capability became available: R=100,000 spectroscopy in the mid-infrared. TEXES (see Lacy et al. 2002, PASP, 114, 153) has spatial resolution set by the telescope diffraction limit and operates between 4.5 and 25 microns. Such high spectral and spatial resolution make TEXES well-suited for studying gas composition, temperature, and dynamics using molecular and ionic tracers.

Discovery of massive high-velocity ionized outflow

As part of the Demonstration Science run in July, TEXES mapped the high-mass star forming region W51 IRS2, which has been compared to Orion (see Genzel et al. 1982, ApJ, 255, 527). As described in Lacy et al. (ApJL, submitted), the 0.6" wide slit was stepped across the area of interest, roughly 8" by 12", to produce high spectral and spatial data cubes of the W51 IRS2 region in [Ne II] (λ = 12.8 μm) and [S IV] (λ = 10.5 μm) forbidden lines, along with neighboring continuum. This mapping mode, one of the two standard TEXES science observing modes, is the most efficient method for TEXES to study extended objects.

Most prominent in our maps is a fairly compact region of gas that is blue-shifted with respect to the ambient cloud velocity by roughly 100 km/s. This gas is most prominent in the [S IV] line. We believe the high-velocity material originates near a known, more deeply embedded maser source within the molecular cloud. As the material punches through into the HII region, it becomes ionized and we are able to trace its behavior. The mass flow rate for this material is at least 1.2 x 10^-5 M_☉ / year. Our maps also show ionized gas near the cloud velocity and gas at intermediate velocities that appears to come from the interaction of the jet and the ambient cloud (see figure 1).

A closer look at the dynamics of the ionized material on the cloud surface suggests a flow along the interface of the HII region and the molecular cloud. This is a pattern we have seen toward several compact HII regions (Zhu et al. 2005, ApJ, 631, 381).

Chemical and dynamical analysis of protoplanetary disk gas

Investigations of protoplanetary disk gas have made much use of near-IR CO observations (see Najita et al. 2007, PPV, eds Reipurth, Jewitt, and Keil, University of Arizona Press, Tucson, 507). The transitions are seen in emission and absorption; the large number of rotational states measured allows determination of gas excitation temperatures as well as column densities; and, where available, resolved spectral lines allow for analysis of the region’s dynamics.

Three TEXES projects during the November Science Campaign observing focused on extending the basic technique to other molecules. Broad rotational H_2 O emission was seen in one source; line widths suggest an origin at around 1 AU from the central star. H_2 emission was seen in four sources, arising in either the disk or surrounding envelope. The mid-IR H_2 transitions are better probes of gas with T<1000 K then H_2 lines at shorter wavelengths.

One binary, known to show C_2 H_2, HCN, and CO bandhead absorption in Spitzer IRS data, was detected in H_2 emission as well as C_3 H_2, HCN, NH_3, and HNCO absorption. The C_2 H_2 and HCN lines show asymmetric line profiles (figure 2). The other molecules, which also show strong absorption with intriguing line profiles, are only seen with TEXES and its high spectral resolution. The high spatial resolution allowed each component to be observed separately in order to determine which line-of-sight contained the absorption.

TEXES and Gemini

TEXES was offered to the Gemini community as a result of the “Aspen” instrumentation process and its recommendation that Gemini provide high spectral resolution in the mid-infrared. A total of 15 PIs requested almost 40 nights of TEXES time for 2006B.

As per the agreement with Gemini, TEXES was open for use by the entire community and all time was awarded through the TAC. The TEXES team would like to continue working at Gemini in 2007B and beyond, but no decision has been made at this time. For details regarding TEXES, its capabilities, and its availability, see www.gemini.edu/sciops/instruments/texes/TexesIndex.html, or contact the author at mjrichter@ucdavis.edu.

Figure 1: TEXES observations of [SIV] (λ=10.5 μm) emission from the W51 IRS2 region. The image comes from a slit scan covering 10" by 7" with spatial resolution of 0.3". The colors (see www.noao.edu/noao/noaonews/mar07/) represent different gas components as identified by their velocities: the cloud surface (+30 to +80 km/s; red), partially accelerated gas (-25 to +30 km/s; green), and the high velocity jet (-80 to -25 km/s).

Figure 2: Examples of TEXES molecular absorption toward a low-mass star with a disk. Unlike the Spitzer IRS spectra for this binary target, these data spectrally and spatially resolve the absorption.