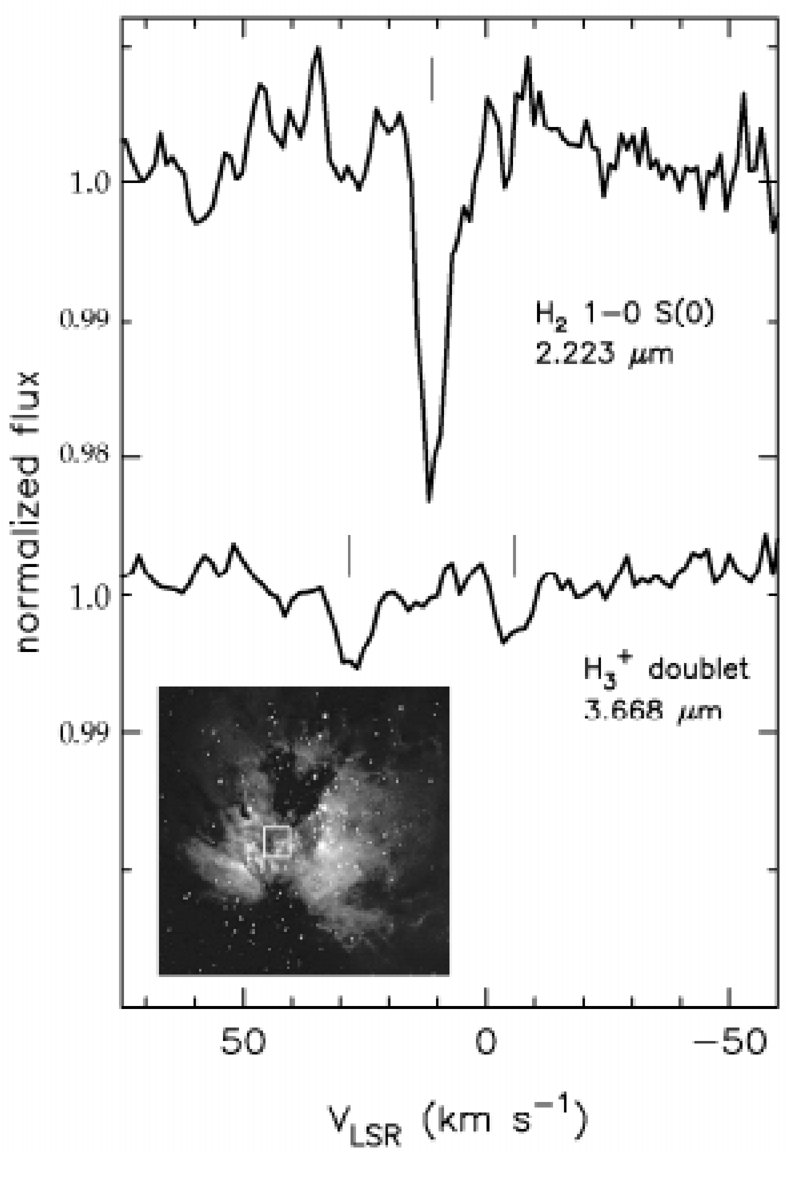
A Nebulous, but Absorbing Probe

Based on a Solicited Contribution from Craig Kulesa

Craig Kulesa (Arizona) and John Black (Onsala Space Observatory) are taking advantage of the unique combination of high resolution and sensitivity afforded by NOAO's Phoenix spectrometer and the 2.1-m telescope at Kitt Peak to probe the intervening interstellar and circumstellar gas towards a sample of luminous young stellar objects embedded in molecular clouds. Their infrared spectroscopic study has produced the first direct, simultaneous observations of cold molecular hydrogen (H_2), the pivotal molecular ion H_3^+, and CO in several isotopes. These measurements, which critically test both theoretical models and microwave observations of molecular clouds, provide unique insight into the physical properties of star-forming regions.



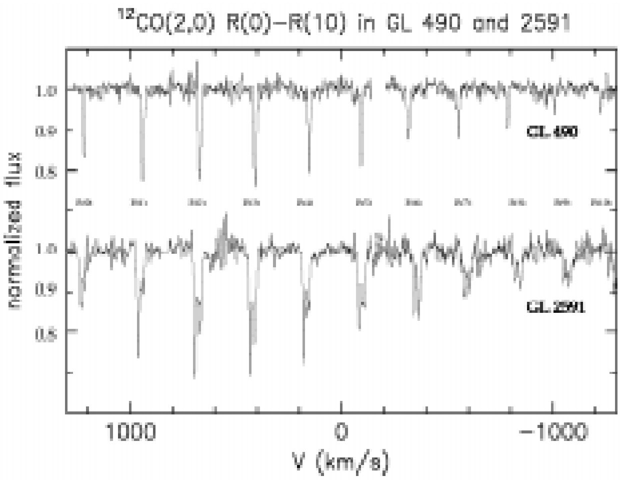
Both H_2, the dominant constituent of molecular clouds, and the pivotal molecular ion H_3^+, are detected in absorption along a line of sight through the Flame Nebula, NGC 2024 (JHK composite image; spectrum taken taken at the location marked by the box). Vertical dashes indicate the expected locations of the absorption lines. The column densities represented by these observations are 3.5×10^{22} and 9.5×10^{12} cm^{-2} for H_2 and H_3^+, respectively.

continued

Although infrared H_2 line emission is now routinely observed in very energetic molecular environments, the ubiquitous H_2 molecule's widely spaced rotational energy levels and lack of permanent dipole moment renders it essentially invisible at the cold temperatures that prevail in dense molecular clouds. With the advent of the high-resolution infrared spectrometer Phoenix, it is now possible to detect the same infrared transitions of cold H_2 in *absorption* towards bright infrared continuum sources embedded deeply within molecular material. Comparison of the abundance of H_2 with other common tracers of molecular material, like CO, is of critical importance to understanding the physical structure and mass content of molecular clouds in both the Milky Way and external galaxies. Of the lines of sight observed so far, $[CO/H_2]$ ranges from $(1\text{-}5) \times 10^{-4}$, a significant departure from an often-assumed value of 8×10^{-5}.

The pivotal molecular ion H_3^+ has long been predicted to be the cornerstone for the ion-molecule chemistry that is partly responsible for forming about 120 known molecules in molecular clouds. However H_3^+, which, like H_2, lacks a permitted radio spectrum, has also eluded detection until quite recently. The measured abundances of H_3^+ are in good agreement with the abundances of observed species that stem from the existence of H_3^+ and generally confirm model expectations of gas phase chemistry in dense molecular clouds. Furthermore, these observations allow a direct determination of the cosmic ray ionization rate of H_2. This parameter is a critical parameter for physical and chemical models of molecular clouds, since cosmic ray ionization is the dominant heating source in the UV-shielded cores of dense clouds. These observations with Phoenix also constrain the formation processes of warm H_2O as measured by the Infrared Space Observatory (ISO) and the Submillimeter Wave Astronomy Satellite (SWAS) for at least two sources.

Observations of CO can be performed using the same infrared absorption techniques, a procedure that has important advantages over observing CO in emissions at [sub]millimeter wavelengths. In the infrared, an entire CO rotational-vibrational band spectrum can be obtained in a single integration, and all observations correspond to the same milli-arcsecond pencil-beam column of molecular gas. Physical conditions and abundances derived with this technique are more accurate and complete than those typically derived from single-dish radio observations.



CO spectra obtained with Phoenix highlight the power of measuring physical conditions and chemical abundances of star-forming regions in the infrared. The high spectral resolution of Phoenix separates the ambient molecular cloud from molecular outflows in GL 2591, and an excitation analysis using the large number of lines uncovers multiple temperature components in both sources, even when kinematically indistinct.

These observations represent the first simultaneous detections of cold H_2, H_3^+ and CO in a sample of dense molecular clouds where other species are already well measured. Follow-up spectroscopy and imaging at infrared and submillimeter wavelengths is now underway to map the environments surrounding these pencil-beam lines of sight to gain a more comprehensive understanding of the physical structure of molecular clouds and the evolution of the star-forming regions within them.

For more information about this project, see *http://loke.as.arizona.edu/~ckulesa/research/*.

A Deep Ecliptic Survey for Kuiper Belt Objects

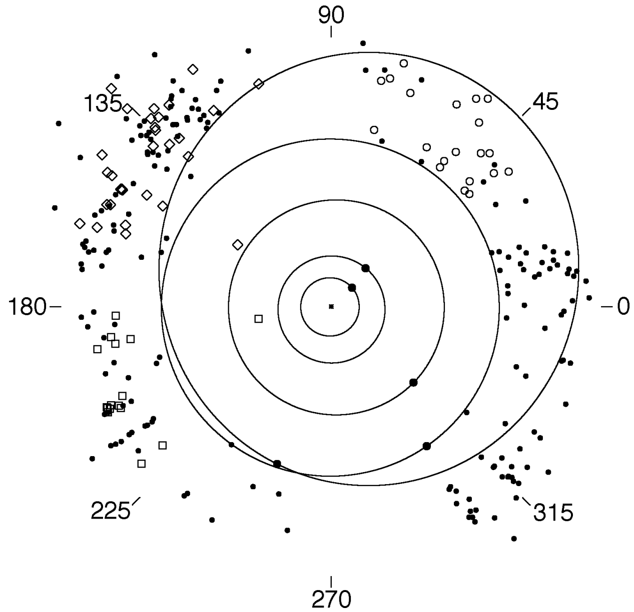
Based on a Solicited Contribution from Marc W. Buie

Marc Buie, Robert Millis, and Larry Wasserman (Lowell Observatory); Jim Elliot (MIT); and Mark Wagner (OSU) are using the KPNO Mosaic camera with the Mayall 4-m telescope to identify Kuiper Belt Objects (KBOs, also known as Trans-Neptunian Objects). The goals of their survey are to answer several fundamental scientific questions:

- What is the spatial distribution of KBOs?
- What are the relative proportions of these bodies in resonant, non-resonant, and scattered orbits?
- What are the physical properties of Kuiper Belt Objects?
- Can the Kuiper Belt be used to understand circumstellar dust disks?

The large area surveyed, combined with the sensitivity of the Mosaic camera, enables the discovery of 15 to 20 new KBOs on each clear night at the 4-m, the raw data necessary to address these questions by acquiring a statistically large sample of KBOs.

The discovery of the Kuiper Belt is an exciting development in planetary astronomy. A vast region beyond Neptune, once thought to be essentially empty except for Pluto and its satellite, Charon, is now known to be populated by $\approx 10^5$ bodies. Most KBOs are asteroidal in size, but a few could be comparable to, or even larger than, Pluto. The 250+ KBOs discovered to date display very interesting dynamical properties; their extremely broad range of observed colors promises remarkable physical properties, as well.



Positions of all Kuiper Belt Objects known to date are plotted at their discovery epochs with respect to the orbits of the outer planets. The numbers indicate ecliptic longitude. Large-scale angular inhomogeneities reflect the locations of the search fields.

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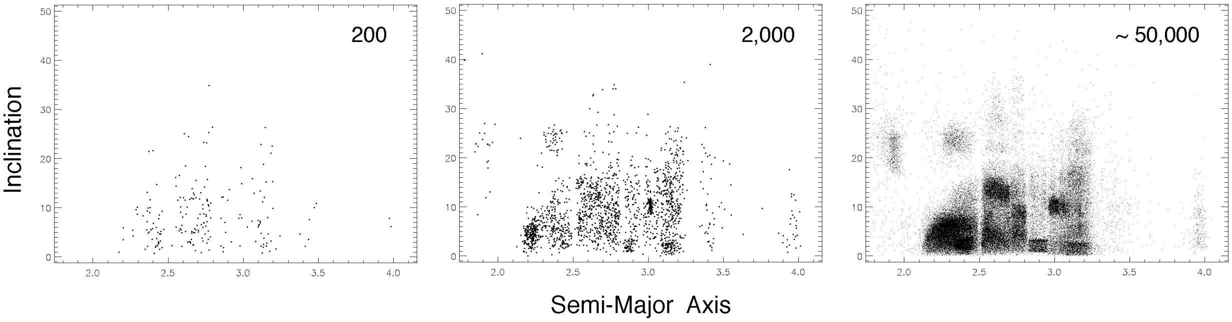
It is now realized that the Kuiper Belt is likely to be analogous to the planet-forming circumstellar dust disks seen around other stars. This tie-in comes from noting that circumstellar dust in some cases must be continuously supplied, presumably from a population of colliding bodies. Our own Kuiper Belt may allow study of the source regions for that dust, while observations around other stars show the end product of collisional grinding. Tying these end-member observations together requires understanding the full dynamical state of the outer solar system through the discovery and follow-up of many more KBOs. In particular, most of the properties of KBOs, and the belt itself, may ultimately be tied to the importance of collisional excitations within the belt.



Like that for the main belt asteroids, the dynamics of the Kuiper Belt Objects will only be revealed through orbital parameters of an extremely large number of objects. The left-hand panel, which shows parameters for the first 200 asteroids discovered, is comparable to our knowledge of KBOs today. The center panel is the result for the first 2,000 asteroids known, i.e., our view of the main belt in the early 1980s. The right-hand panel shows that different families of asteroids are readily revealed in the main belt after some 50,000 main belt asteroids are studied.

The observations by the Lowell group, combined with those from other observers, have begun to outline the Kuiper Belt population. Analogy with the main belt asteroids illustrates the critical importance of sampling a large number of objects. Twenty years ago it was tempting to think that the dynamical distribution of the main belt asteroids was fully understood. However, the full complexity of the gravitational sculpting in the main belt is only now being revealed through orbits of nearly 50,000 asteroids. An analogous plot with 50,000 KBOs will be just as revealing.

A unique aspect of the Buie et al. survey is the use of a powerful new technique of searching for moving objects. Though they make extensive use of automatic computer source detection, they also use direct visual examination of all data; the human brain is a powerful tool for identifying image motion. In the past, the most commonly used technique for finding moving objects was to blink two or more registered images. In fact, it was this precise technique that was used to discover Pluto. Buie et al. code the images with color. They load the first epoch image into the red plane of an image display. The second epoch image is loaded into the blue and green planes of the display. Once the images are registered, all stationary objects will be displayed in shades of gray. Any object that moves creates a red/cyan image pair that is readily distinguishable from all the gray objects.

The beauty of this technique is that it takes advantage of the built-in image processing abilities of the human brain, rather than relying so much on memory, as is required for traditional blinking. The color-blink method is insensitive to CCD artifacts and blemishes as well as cosmic ray strikes. Most of the time it is not even necessary to perform the normal bias subtraction and flat-fielding steps.

continued

Another distinct advantage is that it only needs two frames; most computer-based search algorithms need three or four frames to function reliably. The reduced number of frames allows much more sky to be searched with the Mosaic camera.

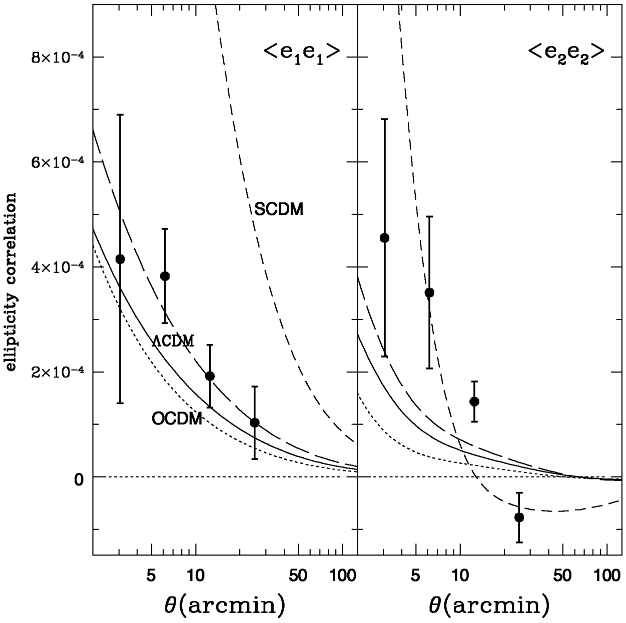
Finding the objects with Mosaic and color-blinking is not enough. To fully understand the discovered objects, their orbits need to be determined. Most of the discovery verification images are taken with WIYN, benefiting greatly from the WIYNQ experiment. In addition, the Lowell group is being helped as well by other investigators using their own telescopes. The process of follow-up and orbit refinement is now the limiting step in the study of the distribution of KBOs.

Cosmic Shear Surely Seen!

Based on a Solicited Contribution from David Wittman

David Wittman, Tony Tyson, and David Kirkman (Lucent Technologies); Ian Dell'Antonio (NOAO); and Gary Bernstein (Michigan) have used the CTIO 4-m telescope to make the first measurement of cosmic shear. Cosmic shear occurs when weak gravitational lensing by large-scale variations in the local matter density causes the ellipticities of background galaxies to be correlated over the sky. The correlation strength as a function of angular scale constrains cosmological parameters such as Ω_{matter} and Ω_Λ; measured accurately enough, it should reveal the mass power spectrum in detail. Attempts to measure this effect have been made since 1967, but only null results were obtained. Now, however, deep imaging over wide fields with cameras of mosaiced CCDs enables careful control of systematic errors.

Wittman et al. used the Big Throughput Camera (BTC), a mosaic of four back-illuminated 2K × 4K CCDs built by Tyson and Bernstein, which was operated as a user instrument at the Blanco 4-m from 1997A through 1999A. They imaged three large (42′ square) widely separated "blank" fields (i.e., containing no known mass concentration) in 1997 and 1998. To reduce systematic errors due to point-spread function anisotropy (the dominant source of error), the group convolved the images with position-dependent elliptical kernels to produce exquisitely round PSFs at all positions.



Autocorrelations for each of the two ellipticity components depend on the redshift of the source galaxies and on the cosmological model. The measured correlations are plotted here with the predictions of three cosmologies for our best estimate of the source redshift distribution: cosmological constant cold dark matter universe (ΛCDM, solid line), standard cold dark matter universe (SCDM, short dash), and open cold dark matter universe (OCDM, dotted line). The long-dash line shows the effect of a 20% error in the mean source redshift for ΛCDM. A cosmological model must match both autocorrelations; SCDM is ruled out at many sigma by $<e_1e_1>$. ΛCDM and OCDM match $<e_1e_1>$, where $e_1 = e\cos(2\theta)$, very well and are consistent with $<e_2e_2>$, where $e_2 = e\sin(2\theta)$ at the 3-σ level. The cross-correlation $<e_1e_2>$ (not shown) is consistent with zero, as expected in the absence of systematic error. The Deep Lens Survey now in progress will provide a much stricter test of cosmological models, or suggest the need for new models.

continued

The images were stacked and convolved again to eliminate any PSF anisotropy due to slight registration errors. The final images each contained ~ 150,000 galaxies down to R=26, of which ~ 45,000 in each field survived a magnitude cut ($23<R<26$), to eliminate as many foreground galaxies as possible and quality checks on their ellipticity measurements.

Angular correlations of galaxy ellipticity in each field revealed a signature of weak gravitational lensing by large-scale structure. Using the mean and the RMS of the three independent fields, the detection was 4σ in one angular separation bin for each of two independent correlation functions (the two functions stem from treating ellipticity as a pseudo-vector with two components $e\cos(2\theta)$ and $e\sin(2\theta)$, where e is the scalar ellipticity and θ is the position angle). The measurements agree roughly with a Universe having a cosmological constant Λ and with an open Universe, but rule out a standard cold-dark-matter Universe. Three other groups subsequently submitted cosmic shear papers in agreement with this measurement. The indication of a low Ω_{matter} universe is in agreement with a remarkable array of independent observations, including high-redshift supernovae and the cosmic microwave background. Surveys are now underway to improve the accuracy of cosmic shear measurements. Comparison of improved CMB and cosmic shear measurements will provide stringent tests of the underlying assumptions in cosmology and perhaps suggest new models.

As described in *NOAO Newsletter* No. 61 ("A Shear Way to Find Dark Matter—and Transients Too!"), one such survey is being carried out at NOAO by Tyson, Dell'Antonio, and Wittman. One of the surveys approved in the first year of survey proposals, this project will image seven 2-degree square fields in BVRz´ over four years with Mosaic cameras on the CTIO and KPNO 4-m telescopes. With a total exposure time of 18,000 seconds in R and 12,000 seconds in BRz´, the group will assign photometric redshifts to source galaxies and study the evolution of structure over time by separating the sources into discrete redshift bins on the order of 0.3 in z.

In addition, in the spirit of making immediate best use of the wide-field survey, the group is trying to maximize the scientific return on the data by searching for transients (supernovae and perhaps new classes of bursters, as well as asteroids and Kuiper Belt objects) as the data come in, and by releasing the data six months after completion of each 40´ square subfield. The first observing season is done, with 19 of the total of 86 nights completed. Check *http://dls.bell-labs.com* for progress updates and release schedule. Also, anyone with a desire to follow up on interesting transients should contact the team (*whittman@physics.bell-labs.com*).

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FeH—An Emerging Magnetic Probe for Sunspots and Cool Stars

Michael Dulick and Jeff A. Valenti

The McMath-Pierce Fourier transform spectrometer (FTS) enables the full potential of FeH to be used as a critical diagnostic of magnetic fields in cool stars. Wing et al. (1977, *ApJ* 216, 659) were the first to provide a convincing detection of FeH in sunspots and cool stars. Interest in the Zeeman response of FeH shortly followed, when the investigators commented on the unusual "square-like" profiles of the FeH rotational lines in the sunspot spectrum, implying possible unresolved Zeeman structure. Use of FeH as a magnetic probe was rekindled in the mid-1990s by stellar astronomers concerned with the existence of magnetic fields in very cool main-sequence and brown dwarf stars, and with the role that magnetic fields play in the coronal heating of G and K dwarfs.

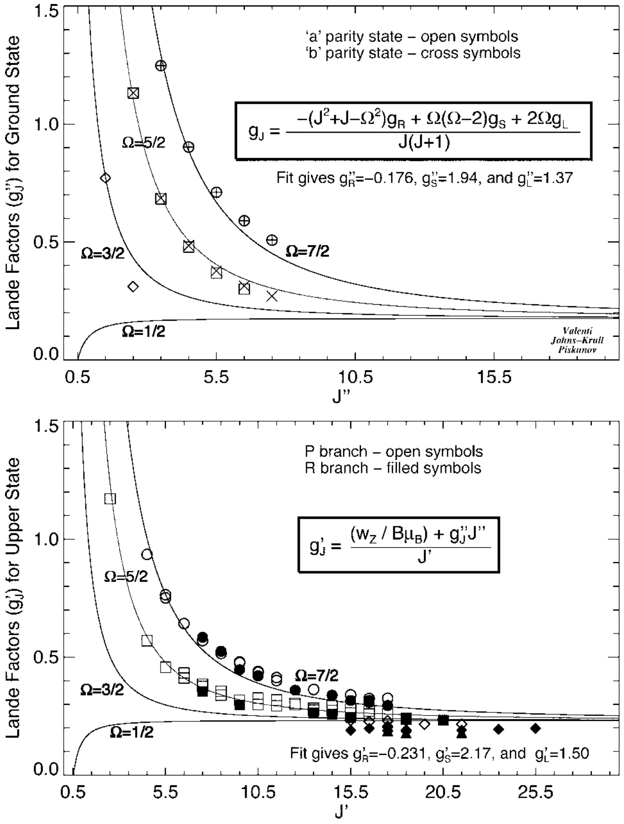
continued

Spectra of cooler stars (T<3500 K) are generally devoid of strong Zeeman-active atomic lines. Instead, the spectra are often characterized by their richness in molecular band structure. Among the diatomics present in these spectra, FeH perhaps offers the best hope of measuring magnetic fields in these stars. The prominent 989.6 nm band (a $^4\Delta$ - $^4\Delta$ 0-0 transition) is present in the region of this spectrum that is virtually free of atmospheric absorption lines. Moreover, the combination of wide-open rotational structure and large Zeeman broadening allows the Zeeman measurements to be performed with spectrometers at moderate resolving powers of 50000.

The possibility of using FeH to measure magnetic fields was advanced by the Wallace et al. sunspot atlas for the red and infrared (1998, *NSO Technical Report* #98-002). From an archived high-resolution sunspot spectrum taken during the 1981 solar maximum with the McMath-Pierce Fourier Transform Spectrometer (FTS), Wallace et al. were able to measure a fair number of partially resolved Zeeman-broadened rotational linewidths in the eight P and R branches of the 989.6 nm band. These measurements represented the only available Zeeman data for FeH. Unfortunately, the data set was just too complicated to extract any meaningful information with regard to Landé g_J factors, which allow magnetic field strengths to be deduced directly from measured Zeeman pattern splittings.

This setback was, however, short lived. In 1998, John M. Brown (Oxford) made very high-precision laboratory measurements of Landé factors in the $^4\Delta$ ground state. Since this state coincides with the lower state of the 989.6 nm band, the sunspot data could finally be interpreted. Valenti and Dulick proceeded to construct a $^4\Delta$ Zeeman Hamiltonian model which allowed the Brown data to be reduced to a single empirical formula. This in turn provided the opportunity to extrapolate the data over the full range of observed rotational levels in the sunspot data. With the measured Zeeman widths from the McMath-Pierce FTS sunspot data, a similiar formula for g_J in the upper state was also derived.

Much of this can be attributed to perturbations in both the lower and upper states by neighboring electronic states. More extensive laboratory measurements are needed to incorporate these perturbations into the model. Such measurements involving the McMath-Pierce FTS are planned for the upcoming year. Nevertheless, the quality of these preliminary results is sufficiently good to the extent that attempts at measuring magnetic fields using FeH are already underway for a small number of active K and M dwarf stars (Valenti, Johns-Krull, Piskunov).



The results of the analysis are summarized in the figure. The smooth curves represent the model results, while the open and filled symbols denote the experimental data. Overall agreement is reasonably good; however, the residuals do reveal, in certain instances, a tendency either to underestimate or overestimate the g_J's in the higher rotational levels.