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Solar Environmental Disturbances

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14. ABSTRACT

Solar activity refers to a variety of non-thermal phenomena seated in theSun's outer layers. Many aspects of solar activity exhibit pronounced, and sometimes explosive, temporal variability. The aim of this task has been to explore the basic physics of the sun that leads to the ultimate production of activity. We have investigated processes occurring below the visible surface of the sun, those seen at the visible surface (the photosphere) the variation of processes with height in the photosphere, processes seen in the middle atmosphere (chromosphere), the variation up to and into the upper atmosphere (the corona) and effects on the interplanetary medium that lead to terrestrial and near-terrestrial effects (space weather). We have sought explanations for how these physical processes affect the production of solar activity, both on short and long time scales.

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1. INTRODUCTION

Solar activity is a term used to designate a variety of non-thermal phenomena seated in the Sun's outer layers. Many aspects of solar activity are distinguished by pronounced, and sometimes explosive, temporal variability. Solar activity is the fundamental driver of the space weather experienced in the near-Earth space environment.

The damaging effects of the explosive events associated with solar activity can be very costly. Solar storms kill satellites, disrupt RF communication, degrade satellite orbits, corrupt GPS navigation and position measurements, and increase radiation doses to humans in space. Solar explosive events produce intense electromagnetic radiation from radio to x-ray wavelengths, large energetic particle fluxes, and vast mass ejecta. Of these three, electromagnetic radiation arrives first at Earth, followed closely by the relativistic particles. These prompt products may be followed at an interval of some 15-60 hours by mass ejecta, which propagate at essentially the solar wind velocity. The effects of solar storms thus last for several days and can involve damaging secondary impacts—e.g., RF communications disruptions reduce effectiveness of military operations.

Although it is impossible to prevent solar storms, it is possible to reduce their impact by appropriate evasive action and adaptation, coupled with informed equipment design. The key is prediction and early warning. Accurate knowledge of an impending flare or CME collision allows system operators to switch to "safe modes" or to send messages that outages are imminent. Launches or astronaut space walks can be rescheduled. As the AF becomes increasingly reliant on space assets, the ability to predict, survive, mitigate, and (perhaps) even exploit space weather will grow in importance. Our success in countering space weather will depend critically on advancing our knowledge of the mechanisms responsible for space weather at its source, namely, solar activity.

The aim of this task has been to explore the basic physics of the sun that leads to the ultimate production of activity. In so doing we have investigated processes occurring below the visible surface of the sun, those seen at the lowest visible regions of the visible surface (the photosphere), the variation of processes with height in the photosphere, processes seen in the middle atmosphere (the chromosphere), the variation up to and into the upper atmosphere (the corona) and effects on the interplanetary medium that lead to terrestrial and near-terrestrial effects (space weather). In all cases we have sought explanations for how these physical processes affect the production of solar activity, both on short and long time scales.

2. LONG-TERM SOLAR ACTIVITY AND VARIABILITY

The possibility that the amplitude of the Sun's cyclic variation might change if viewed away from the ecliptic plane was investigated in detail. Computer modeling showed that the apparent amplitude of the solar cycle would decrease by as much as 40% in chromospheric Ca II K-line emission, while increasing by as much as 80% in white light, as the viewing situation moved toward the Sun's poles. These results offer compelling evidence that solar irradiance variability is a true luminosity effect, and may also help reconcile the discordance between measurements of solar brightness variations and their stellar analogues, which typically seem to have somewhat larger amplitudes.

We have combined observations of about 30 sunlike stars from Mount Wilson, Lowell, and Fairborn Observatories to extend our joint time series to more than 35 years. The full range of variation on the decadal timescale has probably now been observed for most of these stars. Statistical relationships between chromospheric and brightness variability derived earlier have been confirmed and strengthened. The Sun's photometric variation still appears somewhat small in amplitude compared to other stars with similar mean chromospheric activity, even when the large Fairborn sample is incorporated into the analysis. An examination of stellar data for analogues of the solar Maunder Minimum suggests that prior estimates of the solar irradiance excursion between the 17th century Maunder Minimum and the present may have been overstated in some previous studies.

It is shown that the full range of photometric variation has probably now been observed for a majority of the program stars. Twenty-seven stars are deemed variable according to an objective statistical criterion. On a year-to-year timescale, young active stars become fainter when their Ca II emission increases, while older less active stars such as the Sun become brighter when their Ca II emission increases. The Sun's total irradiance variation, scaled to the b and y stellar filter photometry, still appears to be somewhat smaller than stars in our limited sample with similar mean chromospheric activity, but we now regard this discrepancy as probably due mainly to our limited stellar sample.

A spectroscopic survey was made of the Ca II H and K core strengths in a sample of 60 solar-type stars that are members of the solar-age and solar-metallicity open cluster M67. The HK index, defined as the summed H+K core strengths in 1 Ã bandpasses centered on the H and K lines, respectively, was adopted as a measure of the chromospheric activity that is present. We compared the distribution of mean HK index values for the M67 solar-type stars with the variation of this index as measured for the Sun during the contemporary solar cycle. We find that the stellar distribution in our HK index is broader than that for the solar cycle. Approximately 17% of the M67 Sun-like stars exhibit average HK indices that are less than solar minimum. About 7%-12% are characterized by relatively high activity in excess of solar maximum values, while 72%-80% of the solar analogs exhibit Ca II H+K strengths within the range of the modern solar cycle. The ranges given reflect uncertainties in the most representative value of the maximum in the HK index to adopt for the solar cycle variations observed during the period AD 1976-2004. Thus, ~20%-30% of our homogeneous sample of Sun-like stars have mean chromospheric H+K strengths that are outside the range of the contemporary solar cycle. Any cycle-like variability that is present in the M67 solar-type stars appears to be characterized by periods greater than ~6 years. Finally, we estimate a mean chromospheric age for M67 in the range of 3.8-4.3 Gyr.

The results from two long-term studies of chromospheric and photometric activity among Sunlike stars were prepared for publication in FY2006:

1. The results of a spectroscopic survey of the Ca II H&K core strengths in a sample of solar-type members of the solar-age and solar-metallicity open cluster M67 were analyzed. The spectra were obtained over several years with the 3.5-m WIYN telescope on Kitt Peak using the Hydra multi-object spectrograph. The sample consisted of 60 stars in the spectral range F9V – G9V. The HK index, defined as the summed H+K core strengths in 1-Å bands centered on the H & K lines, was adopted to measure chromospheric activity. To gain insight into the range of potential solar activity, the distribution of mean HK index values for the M67 solar-type stars was compared with the variation of this index as measured for the Sun during the current cycle. The stellar distribution was found to be broader than that of the solar cycle. Approximately 17% of the M67 stars exhibit average HK indices that are less than solar minimum. About 7-12% are characterized by activity in excess of solar maximum values, while 72-80% of the M67 solar analog stars exhibit Ca II H+K strengths within the range of the modern solar cycle. The cited ranges reflect uncertainty in the maximum HK index for the solar cycle. In summary, 20-30% of the homogeneous sample of Sunlike stars has mean HK indices outside the range of the contemporary solar cycle. Seasonal variability is also present in the stellar data that is often larger than what is observed on the Sun. Any cyclic activity present in the stellar data appears to be characterized by periods greater than about 6 years. From the data, the chromospheric age for M67 is estimated to be 3.8-4.3 Gyr.

2. The patterns of variation of 32 primarily main sequence Sun-like stars were examined, extending the previous 7–12 year time series to 13–20 years by combining Strömgren b, y photometry from Lowell Observatory with similar data from the Fairborn Observatory. Parallel chromospheric Ca II H & K emission data from the Mount Wilson Observatory span the entire interval. Th
3. e extended data strengthen the relationship between chromospheric and brightness variability derived previously (in 1997). The full range of photometric variation has probably now been observed for a majority of the program stars. Twenty-seven stars were deemed variable according to an objective statistical criterion. On a year-to-year timescale, young active stars become fainter when their Ca II emission increases while older less active stars such as the Sun become brighter when their Ca II emission increases. The Sun's total irradiance variation, scaled to the b and y stellar filter photometry, still appears to be somewhat smaller than stars in this limited sample, but this discrepancy is now regarded as probably due mainly to sample size.

3. SOLAR CYCLE STUDIES

Previous observations of the solar corona indicate that the solar dynamo, which is responsible for the huge variations in solar activity known as the "solar cycle", produces activity at much higher solar latitudes than previously known. This phenomenon has become known as the "Extended solar cycle." The most recent extended cycle observed throughout its entire course was cycle 22, which began 1979 near 70° latitude and ended near the equator 18 years later, in 1996. These high-latitude effects also appeared in the current cycle 23, beginning in 1989 near 70°. Cycle 24 has also now manifested itself near 70° in 1999, and by the end of 2003 it had progressed to 60° latitude. These observations will required modifications of theoretical models of the dynamo that will doubtless lead to improvements in our understanding of how space weather is produced and can be predicted.

Much attention has been focused recently on global warming and possible variations in the transparency of the terrestrial atmosphere that may be a cause or effect of such warming. Since 1983 measurements have been taken at the Sacramento Peak Observatory of the sky brightness (using the Evans Coronal Photometer) and the transparency (using guider voltage from the Evans 40-cm coronagraph as a proxy) at local noon. The sky brightness measures broad-band white light and are calibrated in millionths of the brightness of the photosphere. The transparency (guider voltage) measurements are only relative. There is a strong seasonal variation in the sky brightness, maximizing in April through June, with a minimum approximately 80% lower in November and December. There is a much weaker seasonal variation in transparency of only a few percent, minimizing in July. Major non-seasonal variations in these parameters are due to global volcanic events, such as El Chichon in 1983 and Mt Pinatubo in 1991-1994, that cause a decrease in transparency of up to 30% and an increase in sky brightness. The correlation coefficient of the two data sets is -0.49. This indicates that the events observed are not due to instrumental causes. If we employ annual averages of these parameters in order to remove the seasonal effects, we find that over the last 20 years there has been a linear increase of sky brightness of 51% and a linear decrease of guider voltage is -11%. These are dramatic effects that may be useful in determining the cause of these terrestrial effects that will doubtless affect the tropospheric battlespace.

R. C. Altrock, with J. W. Cook & J. S. Newmark of NRL, completed a comparison of the Sacramento Peak Fe XIV Index with a model index computed from differential emission measure maps. The Sacramento Peak Fe XIV 530.3 nm green line index and a model index time series were compared from the Extreme-ultraviolet Imaging Telescope (EIT) on board the Solar and Heliospheric Observatory (SOHO), for the years 1996-2002, from cycle minimum past the peak of the current activity cycle. A differential emission measure (DEM) map for each day using images from the four channels of EIT at 171Å, 195Å, 284Å, and 304Å was computed and used to calculate a daily synthetic Fe XIV 5303Å intensity image. The Sacramento Peak index is an average intensity, measured using a circular aperture 1.2 arcmin in diameter, sampling the off-limb corona in 3° steps around disk center. It is taken at several different heights beyond the white light limb. The daily index values at 1.15 Ro and at 1.25 Ro from disk center were modeled as the weighted average intensity within an annulus covering 1.11 - 1.19 Ro and 1.21 - 1.29 Ro superposed on the daily synthetic intensity image. When the observed index was compared with the model results, a high correlation of the short-term values was found, but a long-term systematic difference in the absolute values. From an examination of the accuracy of the respective calibrations, it appears that the model results, based on the calibration of the EIT images used to produce the daily DEM maps, are more plausible in absolute value. The Sac Peak calibration 3 sigma fractional error in year 2000, when the differences between model and Sac Peak index values were near-greatest and of order

60%, was itself ± 56%. It is also difficult to understand the time-dependent change in this disagreement. Neither the Sac Peak nor the model index values are perfectly calibrated. While the model index absolute calibration appears to be better supported, the observations must not be undervalued, but this requires a fuller understanding of the Sac Peak instrument calibration. One possibility, suggested by the fact that the disagreement between Sac Peak and model index values is small at minimum activity level in 1996, and larger at times of higher solar activity level, is a nonlinear response by the Sac Peak electronics. This possibility will be investigated in the future.

Observations at 1.15 solar radii of the forbidden coronal lines Fe XIV 530.3 nm and Fe X 637.4 nm obtained at the National Solar Observatory at Sacramento Peak were used to determine the variation of coronal temperature at latitudes above 30° during parts or all of solar activity cycles 21, 22 and 23. Temperatures at latitudes below 30° were not studied, because the technique used to determine the coronal temperature is not applicable in active regions. The Sun's polar temperature was found to vary cyclically from approximately 1.3 to 1.7 MK (millions of Kelvins). The temperatures are similar in both hemispheres. The temperature near solar minimum decreases strongly from mid-latitudes to the poles. The temperature of the corona above 80° latitude generally follows the sunspot cycle, with minima in 1985 and 1995 - 1996 (cf. 1986 and 1996 for the smoothed sunspot number, Rz) and maxima in 1989 and 2000 (cf. 1989 and 2000 for Rz). The temperature of the corona above 30° latitude at solar maximum is nearly uniform; i.e., there is little latitude-dependence. If the maximum temperatures of cycles 22 and 23 are aligned in time (superposed epochs), the average annual N+S temperature (average of the northern and southern hemisphere) in cycle 23 is hotter than that in cycle 22 at all times both above 80° latitude and above 30° latitude. The difference in the average annual N+S maximum temperature between cycles 23 and 22 was 56 kK near the poles and 64 kK for all latitudes above 30°. Cycle 23 was also hotter at mid-latitudes than cycle 22 by 60 kK. The last 3 years of cycle 21 were hotter than the last 3 years of cycle 22. The difference in average annual N+S temperatures at the end of cycles 21 and 22 was 32 kK near the poles and 23 kK for all latitudes above 30°. Cycle 21 was also hotter at mid-latitudes than cycle 22 by at least 90 kK. Thus, there does not seem to be a solar-cycle trend in the low-coronal temperature outside of active regions, unless it is manifested only near solar maximum. The polar temperature cycle is more symmetric than the Rz cycle: the rise and fall times are more nearly equal than for Rz.

Coronal emission generally follows the sunspot cycle at low latitudes. Fe XIV has significant high-latitude emission near solar maximum. Fe X high-latitude emission near solar maximum is weaker. Also in Fe X, there are unexpected episodes of weak emission at and near the poles after solar maximum. They occur during the phase of the solar cycle in which large coronal holes form at the poles and extend down to lower latitudes. This emission could be the signature of these lower-temperature phenomena. Symmetric regions of Fe X emission are also seen in mid-latitudes from 1995 to 1997 and possibly 11 years earlier.

A study of long-term variations of solar coronal rotation was completed. Measurements of Fe XIV (1976-2001) and Fe X (1983-2001) line intensities observed at 1.15 and 1.25

solar radii (Ro) made with the National Solar Observatory/Sacramento Peak 40-cm coronagraph and Emission-Line Coronal Photometer were used. An earlier analysis of Fe XIV data at 1.15 Ro over only one 11-year solar activity cycle (Sime, Fisher and Altrock, 1989, *Astrophys. J.*, **336**, 454) found suggestions of solar-cycle variations in the differential (latitude-dependent) rotation and latitude-averaged-rotation patterns, attributed to the combined effects of large-scale patterns seen in the white-light corona and smaller-scale patterns seen in chromospheric and photospheric rotation. These results were tested over the longer epoch now available. In addition, the Fe XIV 1.15 Ro results were combined with those at 1.25 Ro and with results from the Fe X line to form a global picture of solar rotation throughout the corona over more than two solar cycles. For long-term averages, the corona seen in the Fe XIV and Fe X ions rotates more rigidly than do photospheric sunspots. The coronal rotation rate below 20° latitude is perhaps slightly slower than for sunspots. Both ions show weak differential rotation that may peak near 80° latitude and then decrease toward the poles. However, this high-latitude peak may be due to sensing low-latitude streamers at higher latitudes. Rotation in the north and south hemispheres is statistically identical. There is an indication that the Fe XIV rotation period may increase with height between 40° and 70° latitude. There is also some indication that Fe X may be rotating slower than Fe XIV in the mid-latitude range. This could indicate that structures with lower temperatures rotate at a slower rate. As found in the earlier study, there seems to be very good evidence for solar-cycle-related variation in the rotation of Fe XIV at 1.15 Ro. At latitudes up to about 60°, the rotation varies from essentially rigid near solar minimum to differential in the rising or maximum phase of the cycle in Fe XIV at both 1.15 Ro and 1.25 Ro. At latitudes above 60°, the Fe XIV 1.15 Ro rotation appears to be nearly rigid in the rising or maximum phase and strongly differential near solar minimum, almost exactly out of phase with the low-latitude variation.

Using similar data, the long-term variations of solar coronal Fe XIV (between 1973 and 2002) and Fe X (between 1984 and 2002) fluxes were also studied. A new calibration determination was used to convert relative intensities to absolute intensities. Although the (disk-averaged) sunspot number sometimes reaches zero near solar minimum, the disk-averaged values of Fe XIV and Fe X minimize at 0.5 and 0.3 millionths, respectively. Thus, there is a source of coronal density and heating that is independent of active regions. The 81-day-block-averages (3 rotations) of Fe XIV and Fe X limb flux show similarities with the smoothed sunspot number. In fact, features in the coronal activity cycle closely match features in the sunspot cycle. The first peak of Fe XIV for cycle 21 (there were four) occurred at 1979.9, which matches the sunspot maximum exactly. The preceding minimum for both Fe XIV and sunspots was at 1976.5. After that, in cases where there were two or more coronal maxima, one of those matched the sunspot maximum exactly. The peak-to-peak amplitude of the coronal flux variation is also similar to that of the sunspot number. The amplitude in smoothed sunspot number recently (excluding cycle 23 maximum) is 21, whereas the amplitude in 81-day-averaged limb flux over the same epoch is 16 for Fe XIV and 10 for Fe X.

Our Task provides daily coronal data to 55 SWXS, USAF/NOAA Space Weather Operations, and the world-wide scientific community by email, FTP (ftp ftp.nso.edu, cd pub/corona.maps), through NOAA's "Solar Geophysical Data" (SGD) PDF version (ftp://ftp.ngdc.noaa.gov/STP/SOLAR_DATA/SGD_PDFversion/ or http://sgd.ngdc.noaa.gov/sgd/jsp/solarindex.jsp) and over the World Wide Web (http://www.nso.edu/CORONA). The CORONALERTS email product provides alerts of high-energy Ca XV emission to over 60 customers around the world.

3.1. Solar Torsional Oscillations and Their Relationship to Coronal Activity

Torsional Oscillations were first observed on the surface of the sun as waves of small deviations from differential rotation, which propagate from the pole to the equator over solar-cycle time scales. More recently they have been inferred from observations of solar global oscillations to occur in the convection zone. Long-lived brightenings in the corona have also been observed to propagate from near the poles to the equator over similar time scales. Here we seek evidence of a relationship between torsional oscillations as observed on the surface and in the convection zone and brightenings in the corona. We find that there is an apparent connection between these two phenomena that extends from the equator to latitudes as high as 70° to 80°. Altrock (1997, Solar Phys. **170**, 411) previously observed high-latitude Fe XIV 530.3 nm emission features during solar cycles 21 and 22 at the National Solar Observatory at Sacramento Peak. He found that the observations supported the concept of "Extended" Solar Cycles, which begin every 11 years but last for approximately 18 years. This concept is based on observations by several earlier investigators extending back to 1957 (see Wilson et al., 1988, Nature **333,** 748, for references). Howe et al. (cf. 2000, Astrophys. J. **533**, L163) found that the well-known "Torsional Oscillation" (TO) signal appears in GONG data at the top of the convection zone and extending deeper. Ulrich (2001, Astrophys. J. **560**, 466) discusses observations of TO made in the photosphere at the Mount Wilson Observatory beginning in 1985. Daily scans of the Fe XIV corona are searched for regions of activity. The locations of these regions are recorded as a function of latitude and time. GONG and Mt. Wilson observations are used to locate zones rotating slightly faster or slower than the average differential rotation pattern (TO). Following the concepts of, e.g, Snodgrass (1987, Ap. J., **316,** L91), we test whether the shear zones between the TO represent zones where the magnetic field is concentrated, leading to the formation of activity (we casually use the term "shear" to refer to the boundary between the faster and slower zones). Synoptic maps of temporal averages of the above phenomena are produced and compared. The TO negative-shear zones are shown to be co-located with zones of enhanced coronal emission up to at least 50° in the main branch of the Extended Solar Cycle and also in the zones where the "Rush to the Poles" occur. At the higher latitudes, the negative-shear zones are approximately co-located with regions of convergence of meridional flows as reported by Ulrich and Boyden (2005, Astrophys. J., **620**, L123), which may also play a role in concentrating magnetic field and producing the coronal activity. These phenomena indicate that coronal activity occurring up to 50° and perhaps higher latitudes is related to TO shear and convergence zones, which implies that both of these phenomena are controlled by the solar dynamo.

3.2. Solar Activity Precursors

A study reported on in 2000 to determine the timing and amplitude of the maximum of the 11-year solar activity cycle was compared with current data. Preliminary estimates for solar maximum indicate that it may have occurred between Jun and Aug 1999. In early 1998, this technique gave a prediction of between Jan and Nov 1999, which is the ONLY prediction that would match such an early maximum.

3.3 Meso- and Supergranulation

We and collaborators at Stanford and Lockheed-Martin made the first extensive observations of the birth, death, and evolution of supergranulation and the advection of mesogranulation by supergranule motions. Since supergranules live 1-2 days, it has been virtually impossible, in the 40 years since their discovery, to observe their evolution from ground-based observatories, where observation time is limited to a maximum of 10-12 hours, and observing conditions (seeing) are sufficiently good only a small fraction of that time. Now, with the Solar and Heliospheric Observatory (SOHO) spacecraft, we have observed these phenomena in high-resolution in a 46-hour run, and at low resolution for 62 days. It was found that some supergranules live for 3-4 days, far longer than previously observed. Mesogranules (structures midway in size between granules and supergranules) are seen to be advected (carried along) by the supergranule flows. When a mesogranule reaches the boundary between two supergranules, it is"crushed" to death by the opposing motions of the supergranules. It is seen that the emerging magnetic flux is first "dragged" to the borders of the tiny granules, then, as the granules die (in about 10 minutes), the flux is pushed to mesogranule boundaries, and as these are destroyed in 2-4 hours, the magnetic flux ends up at the borders of the dominating, longer-lived supergranules. These hierarchical convection motions determine the structure of magnetic fields on the Sun.

The MDI instrument on the SOHO satellite obtained a nearly continuous 45.5-hr run in high-resolution mode on 17-18 January 1997, collecting continuum, Dopplergram, and magnetogram images once per minute. This is one of the longest data sets yet obtained in this mode and shows significant evolution of the supergranulation pattern. After allowing for solar rotation within the fixed field of view, an area spanning 17° in latitude and 11° in longitude was extracted that covers the same area of the solar surface for the entire run. From the de-rotated continuum images, we computed flow maps of photospheric motions using local correlation techniques (LCT). Horizontal divergence maps constructed from the flow maps show local maxima of the size of mesogranules (5-10 arcseconds). We interpret these as mesogranules although the LCT flow map resolution (4.8 arcseconds FWHM) may not completely resolve smaller mesogranules. Movies made from the divergence maps clearly show the outward convection (advection) of these mesogranules within each supergranule, and narrow boundaries of negative divergence outlining the supergranules. Several new supergranules are observed forming. These appear as areas of strong divergence that pop up between pre-existing supergranules and grow, pushing their neighbors apart. Others seem to perish between growing neighbors. We also computed the vertical component of vorticity from the flow maps. Movies of this vorticity do not show any obvious patterns.

4. STUDIES OF THE SOLAR SPECTRUM

Changes in disk-integrated Ca-II K-line spectra were compared with changes observed in full-disk K-line spectroheliograms. Disk-integrated K-line spectra have been obtained on a synoptic basis by Task 92VS07COR and the National Solar Observatory (NSO) at both its Kitt Peak and Sacramento Peak sites for the past two solar cycles. NSO also records Ca II K-line spectroheliograms on a daily basis at Sacramento Peak. The disk-integrated observations have been used as a proxy for changes in solar UV and EUV lines that can only be measured from space, as a predictor of satellite drag, to compare the Sun to other active and variable stars and to measure solar differential rotation on the Sun when viewed as a star. The goal of the comparison with the spectroheliograms is to understand and calibrate the causes of change-integrated intensity and changes in the so-called emission index (an integral of the intensity over a 1-Å band centered on the K-line) with changes in plage area and plage brightness integrated over the solar disk have been seen and will be studied further.A former contractor is currently advancing his work on understanding the chromospheric heating of solar activity using data he obtained as a part of his research support when he was contracted to support USAF research. The spectra of doubly ionized calcium (Ca II) at 393.3 nm near line center show distinct multiple reversals, beyond the well-known K1, K2 and K3 reversals. These multiple reversals occur when small scale sub-arcsecond magnetic fields emerge through the chromosphere. The impact of the chromospheric 3-minute oscillations of these reversals is presently unknown. The wavelength location of these multiple reversals occur significantly red-ward of the familiar K3 peak absorption, showing significant chromospheric downflow velocities of 40-50 km/s, indicating shocks.The variation of the large-scale coronal temperature at mid-to-high latitudes over 1.5 solar cycles was studied. Observations at 1.15 solar radii of the forbidden coronal lines Fe XIV 530.3 nm and Fe X 637.4 nm obtained at the National Solar Observatory at Sacramento Peak were used to determine the variation of coronal temperature at high latitudes during solar cycles 22 and 23.Coronal temperature at high-latitudes showed an unexpectedly-large-amplitude variation from solar minimum to solar maximum symmetrically in both hemispheres. The polar temperature varied cyclically from approximately 1.3 to 1.7 MK. The temperature of the corona above 72° latitude generally followed the sunspot cycle, with minima of 1.2-1.3 MK in 1985 and 1995 and maxima of 1.6-1.7 MK in 1989 and over 1.6 MK in cycle 23. The temperature values were similar in both hemispheres. Cycle 22 may have been cooler than cycle 21. A mid-latitude maximum of at least 1.8 MK occurred in 1983 or earlier. During cycle 22 the maximum at the same latitude in 1993 was only 1.69 MK. Cycle 23 will be at least as hot as cycle 22. The 189-day averages of coronal temperature in Table 1 show that (i) polar temperature minimum occurred slightly before Rz minimum, and (ii) polar temperature maximum occurred near Rz maximum. Thus, the polar temperature cycle increased slower (longer rise time) than the Rz cycle. The polar temperatures may have decreased faster (shorter fall time), thus making the polar temperature cycle more symmetric than the sunspot cycle.

Observations of the Fe XIV solar corona are obtained up to three times weekly with the photoelectric coronal photometer at the Evans Solar Facility of the National Solar Observatory at Sacramento Peak. Scans at 0.15 solar radii above the limb show coronal features overlying active regions, prominences, large-scale magnetic field boundaries, etc. Observations approaching solar minimum continue to show coronal activity even when there may be no active regions. A very clear pattern is seen showing emission at latitudes in the vicinity of 40° to 50° near the end of 2006 on days when there is a lack of emission over low-latitude active-region belts. When the emission on these days is averaged, the results shows emission maxima occurring at latitudes varying from 39° to 48°. This seems to imply emission occurring in a dense torus encircling the Sun centered near these latitudes in both hemispheres. Wilcox Solar Observatory synoptic maps of photospheric magnetic fields near end of 2006 show persistent large-scale magnetic field boundaries in the latitude range 40° to 60°. The location of these boundaries for the specific days included in the average of the Fe XIV coronal intensities range from 42° to 52°, thus occupying the same approximate latitudes as the coronal maxima. The cause of the mid-latitude Fe XIV emission near solar minimum appears to be features overlying large scale boundaries of the photospheric magnetic field. Annual averages of the location of Fe XIV emission maxima indicate that solar cycles begin near 70° latitude and end near the equator about 18 years later. This has been referred to as the "Extended" solar cycle. Recent data show that cycle 24 has progressed from 70 degrees to the latitude range 40° to 60° in 2006, near the latitude range occupied by the neutral lines of the photospheric magnetic fields and the daily scans referred to above. The daily coronal scans appear to part of the "Extended" solar cycle. This may indicate a connection between the "Extended" solar cycle and the large scale photospheric magnetic field in the epoch preceding the start of the solar cycle 25. Fe X does not show similar effects, probably due to its much-lower ionization temperature (1 MK vs. 2 MK for Fe XIV) EIT Fe IX image shows coronal maxima occurring at approximately 20 degrees higher latitude than in Fe XIV. This indicates that the coronal hole boundary seen in Fe IX is not the actual magnetic field boundary.

Previous studies of the rotation of the solar corona have found evidence for variations with time in the differential rotation rate similar to what has been referred to as torsional oscillations (zones of faster and slower rotation that migrate toward the equator) in the photosphere and the convection zone. However, the consistent data set of Fe XIV intensities obtained at Sacramento Peak since 1973 has not been exhaustively studied to determine if such oscillations exist. This data set has the advantage that a single photoelectric technique has been used to obtain the data over its entire length, whereas other studies have used data sets compiled from observations obtained with a variety of methods from several observatories. The use of the Sacramento Peak database also has the advantage that the data have been corrected for sky-background variations in real time and thus are very precise over the time required to take a single scan. Altrock (2003, Solar Phys. 213, 23) studied the rotation of the Fe XIV 530.3 nm and Fe X 637.4 nm corona with data obtained at the National Solar Observatory at Sacramento Peak from 1976 (1983 for Fe X) to 2001. He found that for long-term averages the corona rotates more rigidly than features in the lower atmosphere, such as sunspots, but with a detectable differential rotation and a possible acceleration above 80º latitude. However, he did not search for temporal variations in the differential rotation curves that might indicate the continuation of photospheric torsional oscillations (cf. Ulrich, 2001, Astrophys. J. 560, 466) into the corona. We use the same data set referred to above to search for torsional oscillations in the rotation of the corona. The details of the acquisition and treatment of the data are found in the earlier paper. The data used here are averaged over time, latitude and the northern and southern hemispheres in order to decrease the noise. The synodic rotation frequency as a function of latitude determined for 2-year averages from 1976 through 2001 show multiple maxima and minima, indicating the possibility of slow and fast streams. When the 26-year average of rotation is subtracted from each 2-year average, the departures from zero highlight regions of possible torsional oscillations. Positive and negative velocities are then plotted on a synoptic map of latitude versus time and compared with the synoptic map of photospheric torsional oscillations of Ulrich. The coronal velocity map is much noisier than that of the photospheric velocities, due to the very-low signal-to-noise character of the coronal observations. However, throughout the entire time-latitude space of the two velocity fields there is marked similarity between the patterns of variation between the greatly-differing heights in the solar atmosphere. This, combined with other observations that show that torsional oscillations are also seen in the upper convection zone, indicate that this phenomena is indicative of an important solar characteristic extending over orders of magnitude of density in the outer layers of the sun. Further work will be done to characterize the quantitative relationship between these sets of data.

5. PRE-FLARE AND CORONAL MASS EJECTION (CME) SIGNATURES

Previously, K. S. Balasubramaniam, S. L. Keil and L. Milano discovered the presence of surface motion and strong vorticity signatures in an active region that produced flares and coronal mass ejections on April 6 - 7, 1997. The data used in that study was one-minute cadence, full-disk hydrogen-alpha imaging of the solar chromosphere. These surface velocity effects occurred about 20 minutes before the two-ribbon flare and the accompanying mass ejection. This work was extended to several additional active regions to explore the statistical significance of such vorticities. By putting a 2K x 2K CCD camera on the full-disk hydrogen-alpha patrol the cadence of the full disk images was increased to 10 seconds. In addition, the most promising active regions were simultaneously observed with the Sacramento Peak Richard B. Dunn Telescope (RBDT). With the RBDT they obtained magnetograms and Doppler images at a 30-sec cadence and high-resolution g-band (photospheric structure) and H-alpha (chromospheric structure) images at a 5-sec cadence. Using these observations, they have demonstrated that strong vorticities appear before all of the flares and CMEs studied. They will now develop techniques that can be used to exploit continuous data that will be produced by the Improved Solar Observing Optical Network (ISOON).

We worked on developing advanced warning indicators for erupting flares using the vorticity of intensity maps and techniques of destretching. This is a most useful and

productive tool for the prediction of solar activity. Proved that for several different flares there was an advance vorticity
signature that can be extracted about 15-20 minutes before the flare. This can definitely be transitioned to operations to provide advance warning of flares.

We observed several more active regions using the RBDT and Hilltop and measured increases in the vorticity of the flow field prior to solar activity. Confirmed previous results that increased vorticity signatures lead brightness increases seen in H-alpha.

We updated a new technique to determine the timing and amplitude of the maximum of the 11-year solar activity cycle. With more data than previously, we determined the slope of the "Rush to the Poles" more precisely and revised the prediction of solar maximum to between Jan and Apr 2000 with a maximum smoothed sunspot number of 160. This work will improve the ability to understand and predict the major features of the solar activity cycle that so strongly impact USAF systems.

6. THE SOLAR CORONA

A study was made the Fe XIV 530.3 nm ("green line") coronal index (CI) of solar activity for 1998. A systematic increase of CI was observed from January to October 1998. Toward the end of the year the rate of increase slowed dramatically. A rotational period (using the FFT method) of 28.5 days was observed throughout the year; however, subsidiary rotational peaks occurred. They are connected with new regions of activity in the green corona. A comparison of CI with other indices of solar activity (2800 MHz flux, the Wolf sunspot number and the Solar Ultraviolet Spectral Irradiance Monitor Mg II data) shows a very good relation. The remarkable feature for cycle 23 is a very pronounced rotational signal shortly after the cycle beginning. This work was done in collaboration with Drs. M. Rybansky, M. Minarovjech and V. Rusin of the Astronomical Institute of the Slovak Academy of Sciences.

6.1 Observations of the Solar Atmosphere

In collaboration with R. Shine, Z. Frank and T. Tarbell of the Stanford Lockheed Institute for Space Research, Dr. Simon obtained a nearly continuous 7-day set of white light images using the Transition Region and Corona Explorer (TRACE) satellite. A 384x384 arc second field of view was used that tracked solar rotation from Stonyhurst longitudes 45E to 45W along the solar equator. Images were taken every minute over most of the interval. The largest temporal gap was 45m and there were only 9 gaps longer than 10m. The area was mostly free of active regions. These images are broad band white light with 0.5 arc second pixels. Granulation is well defined, and they used local correlation techniques (LCT) to compute flow maps of the horizontal velocities with a resolution of about 5 arc seconds. The flow map resolution and quality suffer somewhat near the longitude extrema but the maps are usable throughout the 7 days to define supergranules and mesogranules. They compute horizontal divergence to study the motions of mesogranules and the evolution and lifetime of supergranules. When enough telemetry capacity was available, they also obtained co-spatial images in the TRACE Fe IX/X 17.1

nm channel and the 160 nm channel. They use these to study the response of the corona and chromosphere to the photospheric motions.

6.2 Replenishment of the Solar Surface Magnetic Field

Dr. Simon, in collaboration with A. M. Title of Lockheed-Martin Advanced Technology Center and N. O. Weiss of the University of Cambridge, discovered how the sun maintains its magnetic network. The MDI experiment on SOHO has revealed a 'magnetic carpet' dominated by the emergence of bipolar magnetic flux in ephemeral active regions, which subsequently split into small flux elements that drift into the magnetic network. The effects of granular and supergranular convection on these flux elements are represented here by kinematic modeling. Elementary flux tubes are transported passively by the supergranular flow, while experiencing small random displacements produced by granulation. They end up in the magnetic network that surrounds the supergranules, where they eventually meet oppositely directed fields and are annihilated. The model calculations show that the total unsigned magnetic flux will decay within a few days unless it is continually replenished. A statistically steady state with a total unsigned flux of 2-3 x 10^{23} Mx over the whole solar surface can be maintained if bipolar flux emerges at a rate of 7 x 10^{22} Mx/day, as indicated by published measurements of the rate at which ephemeral active regions appear.

Predicting the date for the maximum of the 11-year solar activity cycle is important to space-system designers, satellite operators, and space weather forecasting. Such predictions are often based on phenomena occurring at or before the solar-cycle minimum preceding the maximum in question. However, another indicator of the timing of activity maximum occurs during the rise phase of the solar cycle. A study of coronal emission observations made at the National Solar Observatory at Sacramento Peak has shown that, prior to solar maximum, distinctive coronal features appear above 50° latitude in both solar hemispheres and begin to move towards the poles at a rate of 8° - 11° per year. This motion is maintained for a period of 3 or 4 years, after which the emission features disappear. This phenomenon is called the "Rush to the Poles." The maximum of solar activity, measured by sunspot number, occurs some 17-21 months before the features reach the poles. In 1997, early in cycle 23, coronal emission features first appeared near 55° latitude, and began to move towards the poles. Using historical data from the two previous cycles, we examined how the use of progressively more data from cycle 23 affected the prediction of the date of solar maximum. The principal conclusion was that the date of solar maximum for cycle 23 (2000.3) could have been predicted to within 6 months as early as 1997. When the Rush to the Poles begins again later this decade, the average parameters for cycles 21-23 will be used to predict the date for the maximum of cycle 24.

Observations of coronal emission obtained at the National Solar Observatory at Sacramento Peak have been used to determine the coronal temperature at high solar latitudes. This temperature shows an unexpectedly-large amplitude variation from solar minimum to solar maximum. The polar temperature varies cyclically from approximately 1.3 to 1.7 MK in both hemispheres. The temperature of the corona above 80° solar latitude closely follows the sunspot cycle. The temperature of the corona above 30°

latitude at solar maximum is nearly uniform; i.e., there is little latitude-dependence. In contrast, the temperature near solar minimum decreases strongly from mid-latitudes to the poles. The maximum temperature was higher in solar cycle 23 than in solar cycle 22. Indeed, if the maximum temperatures of cycles 22 and 23 are aligned in time (superposed epochs), the annual hemispherical average temperature in cycle 23 was hotter than that in cycle 22 at all times above 80° latitude, and for all except the early rise time above 30° latitude.

7. STRUCTURE OF SUNSPOTS

We completed a 3-year project on the fine-structure in sunspots. Sunspots are the loci of most solar activity events, and have the strongest magnetic fields on the Sun. These fields suppress the Sun's normal convection processes (hence a sunspot is darker than the nearby photosphere). But there exist very tiny convection channels (tubes, plumes, bubbles) in a sunspot where convection breaks through the confines of the magnetic field. Some are called "umbral dots", others "penumbral grains". Because of their small size and short lifetimes, they are extremely hard to observe, but in these studies with the best 11-hour data set ever obtained, We, together with collaborators from Czechoslovakia and Germany, using a Swedish telescope in Spain, have successfully observed and analyzed both of these sunspot phenomena.

7.1 Solar Magnetoconvection

Dr. Simon and Dr. Strous (whom Simon hired for one year at VSBXS with a special Phillips Lab Fellow $100K award) analyzed 62 days of high resolution data from the MDI instrument on the SOHO spacecraft and discovered giant velocity flows which last for at least one month, and range from 200,000 to 600,000 km in size. Their existence had been predicted in 1968 in a theoretical project by Simon and the eminent British astrophysicist Prof. Nigel Weiss, Fellow of the Royal Society (FRS). In that paper they predicted both giant cells and medium-scale motions (mesogranules). The mesogranules were discovered by Simon and colleagues in 1981, but it was not until 1998 that the giant cells were finally seen. To date, four scales of convection have been observed on the Sun (the two mentioned here, plus granulation and supergranulation). Granulation was first seen in 1800, but the other three scales have all been discovered in the last 35 years by Simon and his colleagues at California Institute of Technology, University of Colorado, Stanford University, Lockheed Martin Corporation, Joint Institute for Astrophysics, and the National Solar Observatory

In addition, our task performed thermal studies at the Gemini telescope on Mauna Kea and the Big Bear Solar Observatory that provided “ground truth” data for thermal and seeing models. For the site survey, effort included refining procedures for evaluating and analyzing data produced by the site survey instruments. A technique was developed to infer atmospheric optical turbulence and astronomical seeing from mesoscale meteorological models. This should permit investigation of a full range of atmospheric parameters in arbitrary geographic locations without costly and lengthy field measurements.

We and collaborators in California and the UK continued our theoretical modeling of solar magnetoconvection. We successfully modeled two phenomena which had been long-standing mysteries: a) Motions of supergranules (large solar cellular convective motions) should force all the Sun's magnetic fields into tiny point-like structures. However, the magnetic field forms into a network pattern, and does not degenerate into points. By introducing a small amount of diffusion of the magnetic field due to "jiggling" by the motions of solar granules (small convective cells), the model demonstrated that a network structure can be maintained at the solar surface; b) The Sun seems to "turn over" essentially all of its magnetic field in about two days' time. A steady state exists in which roughly the same amount of old magnetic flux is being destroyed (reconnects) as new flux is emerging. A model was developed that successfully showed how a simple process of emergence and reconnection interacting with supergranular convection can produce such a steady state with the observed turn-over time of two days, and with a network structure closely resembling that seen on the Sun.

7.2. Dynamics of Small Scale Magnetic Elements

K. S. Balasubramaniam collaborated with M. Sigwarth (Kiepenheuer Institut, Germany)and M. Knoelker (High Altitude Observatory, Boulder) on understanding the fine-scale dynamics in magnetic-flux tubes using Zeeman vector polarimetry with the Advanced Stokes Polarimeter at NSO/SP. They discovered that the dynamic behavior of magnetic elements increases dramatically when observing isolated or only weakly-clustered flux tubes outside of active regions. Hints were found that the observed dynamic processes within flux tubes are triggered during the formation of magnetic elements as well as by the stochastic interaction with the granulation and in response to the 5-minute oscillations. The statistical analysis of a large number of Stokes-V profiles from network, intra-network and active-region magnetic fields, and the analysis of individual magnetic structures observed at high temporal resolution reveal dramatic increases in the dynamic behavior and properties with decreasing size/filling factor of the magnetic structures. Vertical up- and downflows exceeding 5 km/s and extreme asymmetries of the V profiles are found to be common for small-scale structures. With respect to an absolute wavelength calibration there is an average downflow of more than 0.5 km/s within the magnetic elements. This discovery hints that the formation of concentrated magnetic elements is indicated by an increasing downflow accompanied by decreasing values of the area and amplitude asymmetries.

7.3. Solar-Wind Forecast Modeling

A study to independently validate the Hakamada-Akasofu-Fry (HAF) kinematic solar wind forecast model was completed. This model is slated to become an operational forecast tool at the Air Force Weather Agency. The AFRL study included the development of a new skill score that incorporates the cost of missed forecasts to the specific end-user of the forecast. Based on the results of this study, the AF now has a basis to accept or reject the HAF model and also to gauge future improvements to the model, including assimilation of data from SMEI.

Dr. C. Fry of Exploration Physics International was selected in July 2003 as an AFRL Distinguished Industry Fellow, under AFOSR sponsorship. During this one-year appointment, his expertise in kinematic solar wind modeling will be applied to the assimilation of SMEI data into operational forecast models. Dr Fry will develop the HAF model to the point where a transition of an operational version of the model or its products will be made to the Air Force Weather Agency by FY05.

8. THE SOLAR RADIO BURST LOCATOR (SRBL)

A Solar Radio Burst Radio Locater (SRBL) radio telescope unit was installed at Sac Peak and began regular operations in March 2004. The SRBL instrument detects microwave bursts that originate at the Sun and indicate the onset of explosive events in the lower corona associated with flares and CMEs. SRBL data consist of spectrograms (frequency-time-power) plots in a number of radio and microwave bands, as well as some directional capability. A program of continuous solar patrol using the Solar Radio Burst Locator to provide microwave spectroscopy data that is complementary to the ISOON telescope system's optical data has been initiated. In addition, we have begun a study on the correlation of microwave bursts to known CME events. We are also creating a database of events that are observed by both the SRBL instrument and the Air Force's operational Radio Solar Telescope Network (RSTN).

Using high resolution spectroscopy at high cadence, we probed oscillatory properties of the large-scale horizontal Evershed-effect flows in sunspots. We employ Doppler measurements in several spectral lines to show that the Evershed flow is modulated at periods lasting a few tens of minutes, at the photosphere and chromosphere. The phase of this modulation is always outward propagating irrespective of whether the spectral line originates in the photosphere or chromosphere. From a power-spectrum analysis, we show that periods of peak power shift to longer periods as magnetic field strength increases (going from the umbra to the outer penumbra), at photospheric levels. At the chromosphere the periods shift to longer periods as the magnetic field shifts from stronger to weaker fields.

9. STUDENT ADVISING

In conjunction with an NSO scientist, Dr. Dalrymple is advising Maj. Dave Byers, an Air Force Ph.D. student studying photospheric precursors of solar flares. This work builds upon previous NSO studies that indicate certain photospheric motions correlate with flare activity. The result will be improved understanding of the relationship between optically-observed solar features and solar flares, with the ultimate goal of flare prediction.

10. ADAPTIVE OPTICS PROGRAM

The National Solar Observatory (NSO) at Sacramento Peak (SP) and VSBXS solar adaptive optics (AO) project passed a major milestone when the control loop for the new system was closed successfully on the optical bench using solar granulation as its target. This is the first AO system to use a correlating Shack-Hartmann wavefront sensor on spatially-extended target scenes. It is also the first AO system to combine the wavefront sensing and reconstruction functions in a modular architecture based on commercially-available DSP (Digital Signal Processor) units. The system is installed at the NSO/SP Richard B. Dunn Solar Telescope. The wavefront sensor camera operates at a 2000 frames/sec update rate. The system was expanded from 24 to 100 subaperture channels.

The solar adaptive optics (AO) system is now available to users of the Richard Dunn Solar Telescope (RDST) at NSO/Sac Peak. The servo loop bandwidth of the system was increased from 25 Hz to about 125 Hz, markedly enhancing the practical utility of the system under ordinary seeing conditions at the RDST. AO is currently revolutionizing high-resolution solar observations from the ground. The first-ever AO-enhanced spectrographic solar observations (including dopplergrams and magnetograms) were obtained during FY00 at the RDST. The spatial resolution of these measurements exceeds anything available elsewhere, even from space (e.g., from SOHO), and represents a major advance. The solar AO system was also deployed successfully at a German solar telescope on the Canary Islands during FY00, thereby demonstrating that the technology is sufficiently flexible and robust to enable use of AO at solar telescopes other than the RDST. In general, solar AO will enhance the performance, productivity, and lifetime of existing ground-based solar telescopes such as the RDST, and represents critical enabling technology justifying the construction of even larger solar telescopes in the future.

11. DESIGN AND USE OF A MAGNETO-OPTICAL FILTER AT THE DUNN SOLAR TELESCOPE

Dr. Alessandro Cacciani of the University "La Sapienza" of Rome, Italy, spent a year here as a Senior NRC Associate funded by AFOSR. He designed and constructed a Magneto-Optical Filter (MOF), which is a very narrowband spectral filter that takes advantage of the Zeeman and related effects to achieve stable and efficient transmission bands. This is a state-of-the-art solar observing instrument that measures velocities and magnetic fields in the solar atmosphere. It allows detailed studies of the buildup of energy in active regions that eventually erupt in a flare or coronal mass ejection. At the RDST he achieved Doppler and magnetic observations with two MOFs in two spectral lines at two levels in the solar atmosphere. The lines used were a strong sodium line that images the upper photosphere of the sun and a weaker potassium line that images the lower photosphere approximately 300 km below the Sodium line. He observed transverse waves surrounding a large sunspot, which were triggered by magnetic Alfven waves. He is analyzing the observations to determine the three-dimensional properties of the physics of energy transport surrounding a sunspot at high spatial and temporal resolution.

12. INSTRUMENT DEVELOPMENT

We worked on development of a microlens array system for fast spectral imaging. This is now a usable instrument configuration that was jointly developed with L. A. Smaldone (AFOSR-supported) and Y. Suematsu. This was a direct result of our high resolution workshop that was partially sponsored by AFOSR.

13. THE IMPROVED SOLAR OBSERVING OPTICAL NETWORK (ISOON)

13.1 Planned System

ISOON was planned as a network of automated solar telescopes and instrumentation being developed by AFRL/VSBS for space weather forecasting. ISOON offered greatly-improved capabilities for detecting, reporting, and predicting solar activity — at reduced cost of operations and maintenance and represented a program in which sustained, basic scientific research in solar physics is resulting in major payoffs to DoD operational capabilities. The domain knowledge leading to ISOON was acquired as an ongoing process, conducted in parallel with technology transition and application products. ISOON, in effect, consists of the sum of the following achievements:

a. Development of methods and instrumentation for measuring and displaying solar magnetic fields, including measurements of both the longitudinal and transverse components ("vector") of the magnetic field

b. Application of narrow-band filter and CCD detector technology, including new methods for characterizing Fabry-Perot (FP) filter optics, controllers, and calibrations (see below).

c. Application of physical models of solar activity processes (MHD modeling) and statistical models (Multivariate Discriminant Analysis) for generating flare forecasts, including energy buildup in stressed magnetic fields, and preflare signatures.

d. Development of data acquisition and processing techniques for solar images, including new techniques for flat fielding, intensity normalization, registration, destretching, frame selection, and registration.

e. Development of near-real-time solar data analysis and display tools, including automatic detection of flare onset and filament eruption, time-lapse playback, image overlays in several wavelengths, Cartesian coordinate transformations, remote control and interactive capabilities.

f. Application of scientific understanding of solar activity phenomena, including parameterization of solar flare events, preflare activity (vector curl maps, derived from non-magnetic-field data), energy buildup, and active region evolution

g. Development of detailed optical, mechanical, and electrical design for ISOON; this is made possible by vast and ongoing experience in solar data acquisition and analysis.

13.2 ISOON Technology Transitions

ISOON has generated a number of specific technology transition items:

1. ISOON functional design, operating parameters, and specifications: Continuous process of transition throughout the year.

2. Consultation for telescopic detection, identification, and tracking of missiles against a star background.

3. Participation in Working Group Report on Orbital Debris; report requested by SAF/AQR, for submission to the Senate Armed Services Committee.

4. Provided field descriptions for Space Architecture Exercise, on topics of statistical methods for forecasting as well as AI methods.

5. Synopsis and prognosis white paper for vector magnetograph upgrade on ISOON.

6. Consultation with Cap D. Byers (AFSPC), via Technical Interchange Program, on topics of solar activity monitoring, prediction, and future instrumentation capabilities.

For ISOON design, we developed limb darkening correction functions for automatic flare patrol software and a scheme for temperature-wavelength-calibrated focus control using the Hartmann test in an automated application. We facilitated the choice of 12-bit intensity images, as a more effective operational capability as well as an essential requirement for scientific study of solar activity. We provided the Space and Missile Systems Center (SMC) with site-specific solar ephemeris and earth-sky geometry data for installation of a new site proposed for Hawaii. We developed data acquisition and processing techniques for solar images, including new techniques for flatfielding, intensity normalization, registration, destretching, frame selection, and registration. We developed near-real time solar data analysis and display tools, including automatic detection of flare onset and filament eruption, time-lapse playback, image overlays in several wavelengths, Cartesian coordinate transformations, remote control and interactive capabilities. We applied narrow-band filter and CCD detector technology to the design, including new methods for characterizing Fabry-Perot filter optics, controllers, and calibrations.

13.3 Other Notable ISOON Program Results

Some specific R&D results or accomplishments owed to the ISOON program:

a. Developed ergonomically-designed software for displays of solar data, analysis tools, and control panels for remotely-commanded telescope systems.

b. Developed a matrix of system availability vs. critical failure and function-restoration intervals, as a tool for assisting management in decisions relating to providing spare parts and instruments.

c. Developed and constructed an optical alignment periscope in support of the ISOON system.

d. Developed a technique for applying the Hartmann focus test to align optical components in a complex telescope system.

e. Designed and constructed a high-speed, photometrically accurate focal-plane shutter covering exposures from 5 milliseconds to infinity, which has the potential for numerous DoD and civilian scientific applications.

Dr. Neidig presented information on DoD and scientific relevancy of the ISOON system for the interagency Science Advisory Board.

a. Development of methods and instrumentation for measuring and displaying solar magnetic fields using fast profile fitting routine.

b. Application of narrow-band filter and CCD detector technology, including new methods for characterizing Fabry-Perot filter optics, controllers, and calibrations. Devised non-invasive diagnostic routines that are likely to be as comprehensive as possible without actual disassembly of the filter. This has profound application potential in ATST and solar physics in general, as the world switches from birefringent filters to Fabry-Perots.

c. Development of near-real time solar data analysis and display tools, including automatic detection of flare onset and filament eruption, time-lapse playback, image overlays in several wavelengths, Cartesian coordinate transformations, remote control and interactive capabilities, automatic contouring and area/length measuring algorithms, improved limb darkening correction functions for automatic flare patrol software.

d. Developed internal reflection suppressor for Fabry-Perot filters used in tandem. High potential payoff with application to ATST

e. Developed tiltable/rotatable optical bench for testing large aperture Fabry-Perot filters under changing gravity vector. High payoff for big projects like ATST.

Although ISOON as a deployed system was cancelled in June 02, the telescope, peripherals, and all unused funds have been transferred to AFRL for use in solar research and limited support of space weather activities. ISOON's greatly improved capability for spectral imaging of solar phenomena is a superb example of the payoff from long-term investment in basic research and instrument development. Some specific R&D results or capabilities derived from the ISOON program include:

a. Demonstrated ability to acquire Helium 10830 images for new techniques in solar coronal hole detection and recurrent geomagnetic disturbance predictions.

b. Development of improved techniques to process, flatfield, register, frame select and display solar images. In particular, the development of a novel flat-fielding algorithm for solar imaging that is 120 times faster than a current widely-accepted technique (i.e., the Kuhn-Lin method) should be noted. The algorithm is applicable to a wide range of imaging problems, including ground- and space-based solar observations, imaging earth objects from space, and digital microscopy.

c. Development of methods and instrumentation for measuring and displaying solar magnetic fields using a non-saturating, Doppler-insensitive, fast profile-fitting procedure that compares favorably to other solar magnetographs. The ISOON system is capable of providing full-disk, high cadence, high-resolution magnetograms for the study of flux emergence, flare precursors, and active region development.

d. Demonstrated application of new procedures for protecting sensitive electronics from lightning damage. Designed, specified, and acquired a fail-safe power system to allow for safe operation and shutdown of ISOON in an autonomous configuration,

e. Investigation of thermal effects and Earth rotational and orbital motions on narrow band imaging system.

f. Major advances in narrow-band Fabry-Perot filter technology were achieved, including new methods for modifying and characterizing Fabry-Perot filter optics, controllers, and calibration methods. An improved method of using multiple Fabry-Perot filters in tandem was demonstrated: fast modulation of the filter cavity. This reduces the effects of polishing error and bandpass mismatch that otherwise plague multi-Fabry-Perot systems. A new, non-invasive diagnostic routine that avoids disassembly of the filter was devised. Overall, this work has profound application potential for solar physics in general, as the world switches from birefringent filters to Fabry-Perots.
g. Demonstrated the concept of a virtual "desktop" solar observatory, remotely commanded, with semi-automatic data analysis and archival. Development of near-real time "ergonomic" solar data analysis and display tools, including automatic detection of flare onset and filament eruption, time-lapse playback, image overlays in several wavelengths, Cartesian coordinate transformations, remote control and interactive capabilities, automatic contouring and area/length measuring algorithms, improved limb darkening correction functions for automatic flare patrol software.
h. Established an ISOON web page featuring latest solar images and movies.

i. Developed and built a second-generation transit accelerometer which monitored the ride conditions of ISOON’s valuable ($300K) and fragile Fabry-Perot filters during shipment between the US and UK. The new accelerometer, based on a PIC 16F877 microcontroller, was packed in the same shipping container at the filters and logged the time and magnitude of significant jarring events over a 2-week period while in transit. During one trip from the UK to US, several 6g+ events were logged by the accelerometer. A subsequent study of the FedEx tracking records showed that this event occurred during customs inspection. When the filter arrived at NSO, it was damaged (but repairable).

j. Acquired and implemented NIST-calibrated photometers for real-time light level monitoring for ISOON.

Other specific R&D results or capabilities derived from the ISOON program include:

a. The discovery of new optical signatures of geo-effective eruptive activity, the detection of which does not require space-based coronagraphs or short wavelength imagers. ISOON images have revealed several cases of wave-like sequential brightenings in the quiet sun chromospheric network which, in combination with nearly simultaneous, widely separated minor flares, mark the near-surface footprint of large scale eruptions and coronal mass ejections. This discovery was selected as a feature article in the NOAO Newsletter No. 75, Sep 03.

b. Routine high-cadence, multi-wavelength solar imaging with photometric errors of less than 1 percent over time and position on the solar disk.

c. The application of narrow-band spectral imaging in measuring supersonic inflows of chromospheric material in the vicinity of sunspots (the inverse Evershed effect), thus allowing routine monitoring of active region atmospheric dynamics.

d. A month-long demonstration of remote operation of the ISOON telescope at Sac Peak, from a computer terminal set up in NOAA's forecast center in Boulder, CO. The system was successfully operated there by non-ISOON personnel, as proof of ISOON's robustness as a deployable system.

e. An active web site (http://www.nso.edu/nsosp/isoon) with current images, movies, and system description. This site recorded 60,509 hits during its first quarter of operation.

f. An impressive ability to measure daily sunspot numbers using a semi-automated routine that is free of observer subjectivity. The National Solar Observatory is presently recording ISOON's sunspot counts in parallel with its own, in anticipation of an eventual replacement of its existing facility and labor intensive procedures.

g. The application of ISOON's all-digital imaging data and display software to generate, for the first time, solar synoptic maps in the hydrogen-alpha line.

h. Proof of the robustness of Fabry-Perot filters in patrol class instruments, while providing improved performance (bandpass, tunability, throughput) over birefringent filters in solar applications. ISOON dual Fabry-Perot filter system has operated for 1.5 years without maintenance or attention other than occasional tuning calibration checks.

13.4 Test Results and Other Scientific Results

A 15-month test and evaluation activity for ISOON was completed on 31 Dec 2003, demonstrating that (1) the ISOON system can meet or exceed specification for 99.6 percent availability, (2) the system can be operated remotely over an internet connection, (3) the system exceeds specifications and all expectations by being able to detect coronal holes, (4) the system is able to detect major coronal blowouts against the solar disk using optical signatures detected via superior imaging and desktop data displays, and (5) the system is robust and easy to maintain. A technical report (AFRL-VS-HA-TR-2004-1108) entitled “ISOON, The Improved Solar Observing Optical Network: Design, Development, and 15 Months of Limited Operation at the National Solar Observatory, Sacramento Peak, New Mexico” describing this work has been prepared and released (to US Government Agencies, only).

ISOON data and analysis were featured in an invited talk at a special session of the American Astronomical Society (Jun 2004), on the topic of the spectacular and unusual (and geo-effective) late-solar-cycle activity in October and November 2003.

After a year of recording ISOON’s sunspot counts in parallel with its own, The National Solar Observatory has ceased its half-century practice of recording and disseminating sunspot drawings in favor of ISOON images and the tabulations performed by ISOON's automated sunspot count and area measurements.

4. ISOON's routine, daily solar irradiance reduction measurements due to sunspot blocking are being included as a product in the National Solar Observatory's synoptic data broadcasts.

A new collaboration with the NSO’s SOLIS project has begun. SOLIS has a state-of-the-art vector magnetograph that complements ISOON’s superb H-alpha, white light, and He-10830 capabilities, together comprising a solar synoptic cluster of the highest quality. Line of sight magnetic field maps from NSO’s SOLIS VSM instrument are routinely incorporated into the ISOON dataset. ISOON data analysis tools have been upgraded to work seamlessly with the SOLIS data. ISOON and SOLIS data have been archived together since 1 Nov 2004.

An online ISOON/SOLIS data archive was constructed in early summer 2005. All of the existing ISOON archival data has been loaded onto the online site, and real-time data is transferred to the online archive as it is obtained. The roughly 350GB (and growing!) online archive is located at ftp://ftp.isoon.nso.edu/isoon/.

Collaboration with the NSO's SOLIS project to obtain magnetograph data that began in 2004, and that complements ISOON's superb H-alpha, white light, and He-10830 capabilities has continued. Line of sight magnetic field maps from NSO's SOLIS VSM instrument are routinely incorporated into the ISOON dataset. ISOON and SOLIS data have been archived together since 1 Nov 2004, and are available as an online resource at ftp://ftp.isoon.nso.edu/isoon/. An active web site (http://www.nso.edu/nsosp/isoon) with current images, movies, and system description has been maintained.

Sequential brightenings of chromospheric network points were observed in a number of eruptive-type flares associated with coronal mass ejections and particle acceleration. The chromospheric points are illuminated in a sequence that propagates at speeds characteristic of Type II radio bursts and the initial stages of mass ejections (several hundred km/s or more). The illuminated points are associated with footpoints of a single magnetic polarity (even in the midst of oppositely poled points that do not brighten), consistent with the disruption of high altitude, global field structures that signify the onset of energetic particle events and geomagnetic disturbances. Thus the detection of flares showing sequential chromospheric brightenings, using semi-autonomous ground-based imaging systems such as ISOON, provides a new capability for early detection of geo-effective solar events.
Observations of a huge Moreton wave event on Oct 29, 2002 has revealed new characteristics of the propagation of flare waves on the solar surface and has shown how several flares in distantly separated active region can be triggered nearly simultaneously by the destabilization of a large coronal structure. ISOON data were used to detect the onset, velocity, and propagation of the flare wave, which bears some similarity to a tsunami as it bends around solar active regions and areas of strong magnetic fields. Detection of the chromospheric imprint of solar global-scale eruptions is important in understanding integrated models of the initiation of solar particle events and mass ejections leading to geomagnetic storms.

14. THE ADVANCED TECHNOLOGY SOLAR TELESCOPE (ATST)

In response to AFOSR urging, our Task, through Dr. Radick's efforts, has significantly increased its support of the National Solar Observatory's (NSO's) Advanced Technology Solar Telescope (ATST) project. Dr. Radick is a Named Collaborator on the NSO's $13M Design and Development award for the ATST from the National Science Foundation. He has also been named Instrument Scientist and Technical Advisor by the NSO for the ATST site selection instrumentation development effort. In this capacity, he has provided urgently-needed scientific and technical leadership. This included identifying, characterizing, and solving several optical and electrical design flaws in the site survey instrumentation, and developing procedures for its validation and field-testing. Site selection and characterization will be critical to the ATST design effort. Dr Radick served as a member of the Site Selection Working Group (SSWG) for the ATST, and as an invited member of a review panel for the NSO's ATST site selection program management, for which he led the preparation of the panel's report. He was also Co-PI for the joint NSO - AFRL/VSBXS solar adaptive optics (AO) project. AO is currently revolutionizing high-resolution solar observations from the ground. In general, solar AO will enhance the performance, productivity, and lifetime of existing ground-based solar telescopes such as the Dunn Solar Telescope, and it represents a key enabling technology for the future construction of even larger solar telescopes such as the ATST.

Our Task has become significantly involved in the Design and Development effort for the ATST, in support of the National Solar Observatory. Task members are serving as Thermal Engineer for the ATST project and Instrument Scientist and Technical Advisor for the ATST site survey. Effort included providing technical leadership. developing thermal models for the heat stop, the primary mirror, the secondary mirror, and the enclosure, as well as planning the future conceptual and detail design efforts and interfacing with other ATST project teams. For the site survey, effort included devising and directing the testing of this instrumentation, and developing procedures for evaluating and analyzing data produced by the site survey instruments. A study to determine the feasibility of forecasting daytime optical turbulence (a.k.a. “seeing”) using mesoscale numerical weather prediction models in support of the ATST site survey was also performed, which offers another method for assessing potential sites for the ATST.

The ATST will be the first major US ground-based solar telescope built in over 30 years, and will provide observations essential for understanding the physical origin of the solar activity that adversely affects AF communications and space systems. When complete, the ATST will image the fine-scale magnetic structures on the surface of the sun that drive solar flares, CMEs, and space weather.

Progress for FY04 included the submission of a highly-rated Construction Proposal to the National Science Foundation, and more detailed engineering advances in essentially every area of the telescope system design.

The Task has contributed significantly to the Design and Development effort for the ATST, in support of the National Solar Observatory. Progress for FY05 included the submission of a highly-rated Cost Proposal to the National Science Foundation, successful engineering reviews for both the enclosure and the primary mirror, and more detailed engineering advances in essentially every area of the telescope system design. At the close of FY05, the NSF Director determined that ATST is “ready” for construction and forwarded this decision to the National Science Board, which will now rank ATST in the MRE queue attach this sentence to the paragraph under 9.3 The ATST Preliminary Design Review was accomplished in Oct. 06.

15. THE SOLAR MASS EJECTION IMAGER (SMEI)

Dr. Radick is PI on the Solar Mass Ejection Imager (SMEI) space experiment. It was delivered in April 2001   to the spacecraft contractor, Spectrum Astro Inc, in Gilbert, Arizona, for integration with the space vehicle This instrument was designed to deliver massive amounts of research-grade data on properties of coronal mass ejections in the interplanetary medium, stellar variability, etc. One outcome will be dramatic improvements in space weather predictions.

Task members are serving as Principal Investigator and Data Scientist for the Solar Mass Ejection Imager (SMEI) space experiment . SMEI was launched on Jan 6, 2003, and has successfully achieved its primary objective of detecting and tracking CMEs as they propagate through interplanetary space.

A study was begun to utilize data from SMEI to provide a photometric whole-sky survey of bright stars. In particular, the unique capabilities of SMEI - namely high photometric accuracy and high observation cadence (once per 100-minute orbit) - allows for temporal tracking of the apparent magnitude of all of the brightest stars in the sky (down to roughly sixth magnitude). A detailed analysis of this database has the potential to determine the characteristics of variable stars in a way that has not been possible to date.

Dr. C. Fry of Exploration Physics International was selected in July 2003 as an AFRL Distinguished Industry Fellow, under AFOSR sponsorship. During this one-year appointment, his expertise in kinematic solar wind modeling was applied to the assimilation of SMEI data into operational forecast models.

Since 2003, SMEI has been recording nearly-full-sky images every orbit (103 minutes) to at least 9th magnitude with 1-degree resolution and transmitting them to Earth. SMEI's main mission was to demonstrate that coronal mass ejections (CMEs) could be detected and tracked through the inner heliosphere en route to Earth to improve space weather forecasts. Besides mission applications, this unique dataset has provided insight into CME morphology and driving forces, interactions between comet tails and the heliosphere, zodiacal light, stellar variability and high altitude auroral phenomena. SMEI also observes asteroids and debris. Future directions for the SMEI research program include tracking CMEs to other planets and searching for streamers and co-rotating interactive regions.

Statistical results of analysis of the SMEI observations of coronal mass ejections (CMEs) traveling through the inner heliosphere show that 139 CMEs were observed during the first 1.5 years of operations, and at least 30 of these CMEs were observed by SMEI to propagate out to 1 AU and beyond and were associated with major geomagnetic storms at Earth. Most of these were observed as frontside halo events by the SOHO LASCO coronagraphs.

Patent

U.S. Letters Patent No. 6,563,572 B1 (AF Invention No. AFB00513) entitled “Correlating Shack-Hartmann Wavefront Sensor”, R. Radick, T. Rimmele, and C. Richards.

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