Solar-cycle Changes in Sunspot Umbral Intensity

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ABSTRACT

The minimum intensities of sunspot umbrae were measured from 1992 through 2003 using the National Solar Observatory Kitt Peak Vacuum Telescope spectromagnetograph data. The resulting 3931 umbral measurements reveal a solar cycle variation in the umbral intensity, with umbrae appearing brighter on average at cycle minimum and darker at cycle maximum. These data show agreement with three other umbral intensity studies, and the similarity with infrared spectroscopic measurements suggests that the mean umbral maximum magnetic field also varies through the solar cycle by 600 Gauss. In agreement with other investigators, the solar cycle variation in the daily average umbral area, the log-normal distribution of umbral area, and the near constancy of the mean umbral radius during the solar cycle are seen in this data.

Subject headings: Sun: activity, solar-cycle Sun: sunspots.

1. Introduction

A recent analysis of infrared spectral data taken by Livingston (Penn & Livingston 2006) revealed on average an increasing umbral brightness, a decreasing magnetic field strength, and a decreasing molecular absorption line depth in over 600 measurements of the darkest sunspot umbral cores made from 1998-2005. This trend roughly agreed with early photometry results from Albregtsen & Maltby (1981) but disagreed with an analysis of archival magnetic field observations of sunspots (Lozitska 2005). The infrared work also seemed to disagree with intensity observations from the SoHO/MDI instrument (Norton & Gilman

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2004; Mathew et al. 2007), although the observations span slightly different times during the solar activity cycle. In an attempt to understand these differences, 3931 measurements of umbral intensities were made during the period from 1992-2003 using archival spectromagnetograph data from the Kitt Peak Vacuum Telescope (KPVT). This analysis represents the largest sample of umbral intensity measurements yet made and covers the longest continuous time period for these types of observations.

The sunspot number and latitude position on the photosphere have long served as important constraints for models of the solar dynamo, and observations of the magnetic field strength in these sunspots has similar potential. The sunspot magnetic field strengths may probe the the source toroidal field within the Sun; sunspot umbral brightness was observed to increase during the solar cycle by Albregtsen & Maltby (1981) and Schüssler (1980) suggested that the source toroidal flux tube was degraded during the solar cycle by radiative heating or shredding by convection. A competing idea is that the sunspot field strength provides information about how magnetic fields erupt from the internal toroidal source field. Work from Schüssler et al. (1994) suggests that flux tubes of a certain magnetic field strength are stable against eruption at low latitudes but not at high latitudes, and so sunspot magnetic fields would vary with latitude during the solar cycle. A latitudinal dependence of umbral brightness was observed by Norton & Gilman (2004). Results from the KPVT data analysis are discussed with regard to these ideas.

2. Observations

The KPVT NASA/NSO Spectromagnetograph (Jones et al. 1992) provided 11 years of full-disk line-of-sight magnetic field measurements by examining the Stokes V spectral profiles of an Fe I absorption line at 868.8nm. This versatile instrument also produced daily maps of the continuum intensity, line depth, width, and Doppler velocity; these data are available on-line at the NSO data archive. For this study we used the full-disk continuum maps, and while the umbral magnetic field values are of great interest, the data reduction techniques used to produce the daily scans do not accurately sample the umbral magnetic fields.

A software package written in *Interactive Data Language* (IDL) from Research Systems, Inc. was used to analyze the archived images. A user simply selected a sunspot region, and the minimum umbral intensity was computed by dividing the intensity in the darkest umbral pixel by the nearby photospheric intensity. The area of the sunspot umbra was also computed by counting the number of pixels whose intensity lay between the minimum and the minimum plus 33% of the difference between the minimum and the photospheric intensity. The user was prompted with an image of the sunspot with the minimum intensity pixel marked, and the umbral pixels highlighted, and asked if the data should be saved. Other parameters, such as umbral position on the disk and the standard deviation of the photospheric pixel intensities were also saved in a data file. In each solar disk map, spots were selected as those which showed some penumbral structure, so pores and smaller spots were not well-sampled. A random check of measurements made by two users showed a standard deviation of 0.005 (in units of the continuum intensity) in the measured sunspot umbral intensities among a common sample of 605 umbral measurements. Most of the measurements were taken from spots with $\mu > 0.6$, (where μ is the cosine of the angle between the observer's line of sight and solar vertical) although some spots appearing closer to the solar limb were also measured.

Since a study of sunspot umbrae has not been made with such scanned spectroscopic data in the past, it is important to compare some basic umbral properties derived from the KPVT data with previous imaging studies. Figure 1 shows the daily total umbral area (in micro-hemispheres) as measured from the KPVT continuum images. The work of Howard, Gilman & Gilman (1984) showed that from 1921 to 1982 the daily total umbral area varied through the sunspot cycle like the Zurich sunspot number. From the figure it is clear that the KPVT data samples one full solar cycle, extending from just after to the maximum of cycle 22 to just after the maximum of cycle 23. The daily umbral area at the peak of cycle 23 is close to the value computed for cycles 17 and 20 in Howard, Gilman & Gilman (1984) in agreement with the fact that the Zurich sunspot numbers for those three cycles were also very similar.

Figure 2 shows the size distribution of the KPVT umbral area and compares them with the function determined by Bogdan et al. (1988) (using the same parameters $< A >= 0.62$ and $\sigma_A = 3.8$). The KPVT umbrae show proportionally fewer small spots compared to a Bogdan log-normal distribution, and this is due to the selection criteria applied to the KPVT data. Sunspots with significant penumbral structure larger than 3 arcseconds were selected for this study, and thus the smallest bin in Figure 2 shows a significant lack of sunspots in our sample compared to the sample from Bogdan et al. (1988). (Excluding the deviant sunspot umbrae in this smallest size bin produces the same intensity time variations seen in Figure 4, within the computed error bars.) Mathew et al. (2007) select sunspots with umbral radii between 5 and 15 arcseconds, corresponding to 27-144 μhemispheres of area at disk center, and the KPVT data set correspond well to the log-normal distribution in this size range.

3. Discussion

Figure 3 shows the umbral intensity measurements plotted against the disk position as measured by μ. The fractional drop in intensity from $1.0 > \mu > 0.4$ is in rough agreement with the models from Maltby et al. (1986); in detail the KPVT intensities drop less steeply at high μ and more steeply at low μ than the Maltby et al. (1986) models. In order to avoid comparison of umbrae with different intensities caused by different μ positions, only umbral measurements made with $\mu > 0.65$ were used in the subsequent time analysis; this threshold included a large fraction (84%) of the total umbral measurements.

As the solar-cycle progresses from beginning to end, the mean latitude of sunspots moves from high latitudes to lower latitudes. After using a threshold of $\mu > 0.65$ the mean annual μ for the umbral measurements was computed. It varies from a low value of $\mu = 0.83$ at the cycle start to a value of $\mu = 0.88$ at the end of the solar cycle. At these positions, the observed average umbral intensities vary by less than 0.5%, and so a time variation of the observed umbral intensity produced by this change in mean position would be expected to have an amplitude less than 0.5%.

Figure 4 shows the average umbral intensity as a function of time from the KPVT observations as a solid line. The mean umbral core intensity is seen to vary from a high of 0.42 at solar cycle minimum to a low of 0.35 at cycle maximum. The error bars on each data point represent the standard error of the mean, and the binning is done for each calendar year. Also shown on this graph are scaled measurements from two previous umbral intensity studies, the work of Norton & Gilman (2004) and Penn & Livingston (2006). Because these two previous studies measured umbral brightness at different wavelengths, these annually averaged umbral intensities are fit with a regression to the annually averaged KPVT intensities. In both cases the fit includes just a zero-point and slope parameter, and the standard errors are used as weights. In the early work of Albregtsen & Maltby (1981) the temporal changes in sunspot umbral brightness have been different at different wavelengths. The ratio of the measured umbral brightness changes with time ($d(\lambda)$) reported by Maltby et al. (1986) were $d(1.54)/d(0.876) = 1.6$ and $d(0.669)/d(0.876) = 1.2$. The ratios obtained in the regressions between Norton & Gilman (2004) and Penn & Livingston (2006) with the KPVT data suggest $d(1.56)/d(0.868) = 1.7$ and $d(0.677)/d(0.868) = 1.2$. This is an excellent agreement with those early multi-wavelength photometric measurements especially considering that three entirely different instruments are compared here, one of which is space-based.

The dashed line in Figure 4 shows the scaled annually averaged umbral intensities from Norton & Gilman (2004) with both hemispheres combined. (The KPVT data show identical temporal behavior in both solar hemispheres.) In this comparison, the few umbral measurements made by Norton & Gilman (2004) in 1996 are not included, but rather only data from 1997-2003 are binned by year to compare with the KPVT measurements. The dash-dotted line shows the intensities measured by Penn & Livingston (2006) using infrared spectra at 1565nm, and here the umbral intensities from 1998 through 2003 are used in the comparison with the KPVT data. The discrepancy between the infrared observations and the KPVT data prior to 2001 is significant only at 2 sigma, because the error on the infrared annual averages are larger during those years as fewer umbrae were observed. Finally, the dotted line is a fit to all the KPVT umbral measurements (not the annual averages) taken from March 1998 through October 2003. This linear fit shows a small intensity change of only 0.12% yr^{-1} in the umbral brightness. Results from Mathew et al. (2007) who examine umbrae from March 1998 through March 2004 using the SoHO/MDI instrument show a temporal change of $0.4\% \pm 0.6\%\ \mathrm{yr}^{-1}$, consistent with the KPVT findings.

While previous authors (Albregtsen & Maltby 1981) made no corrections for telescope stray light in observations made at the 868.8nm wavelength, the recent work of Mathew et al. (2007) using measurements at 676.8nm does make corrections. The KPVT data are not images; rather the solar disk is scanned in four swaths across a spectrograph slit as the spectral cameras are synchronously read in order to build a map of the solar surface. It is not possible to use the shape of the solar limb to determine the stray light influencing the umbral measurement since the limb is scanned at a different time. It is possible to measure the long-term stray light changes in the KPVT data with such limb observations, and while these cannot correct the umbral measurements, similar temporal trends in the stray light and umbral intensities would cast doubt on the umbral measurements. Binning the KPVT stray light measurements into annual bins shows only a weak temporal trend at the 0.5% level which would suggest a slightly stronger intensity modulation of umbral brightness during the solar cycle. The errors in the annually binned umbral intensities are larger than this value and no long-term stray light correction is made in Figure 4.

Magnetic field measurements from Penn & Livingston (2006) revealed a change in the average maximum umbral magnetic field strength from 1998-2006 of about 600 Gauss which were correlated with infrared intensity variations. The excellent agreement between the KPVT and infrared intensity changes is strong evidence that umbral magnetic field also oscillates in strength during the solar cycle, with umbrae showing stronger magnetic fields during sunspot maximum, and weaker magnetic fields at sunspot minimum. An oscillatory change of 600 Gauss during the solar cycle would predict a measurable change in the mean umbral radius, since the observations of Kopp & Rabin (1992) and Brants & Zwaan (1982) show a relation between umbral radius and maximum magnetic field strength. No such umbral radius variation has been observed in previous work (Bogdan et al. 1988) and it is not seen in these KPVT data. As the work of Kopp & Rabin (1992) and Brants & Zwaan

(1982) includes only 35 umbrae, and all the observations were made within two years of sunspot maximum, it is possible that the relationship between umbral radius and maximum field strength varies during the sunspot cycle. An analysis of the KPVT using only sunspots within certain umbral size bins shows the same periodic time behavior as seen in the complete data set (with higher noise levels). Unfortunately no clear change of the relationship between umbral radius and intensity has been seen in the KPVT data. Since the relationship between maximum magnetic field strength and umbral radius likely results from horizontal pressure balance in the photosphere, a fluctuation of this relationship during the solar cycle could only occur if a term in this pressure balance varied with time. The twist of the umbral magnetic fields might provide such a variation (Kopp & Rabin 1992), and while changes in field twists during the solar-cycle have not been observed (Pevtsov, Canfield & Latushko 2001), the measurement error bars remain large. This topic seems appropriate for more study especially in view of numerous recent vector magnetic observations.

The flux tube erosion model of Schüssler (1980) is difficult to reconcile with the KPVT cyclic variation in umbral intensity. The umbral intensity is seen to first decrease and then increase during a solar cycle, and a uniform erosion of the source magnetic flux during the sunspot cycle cannot account for this change. In addition, no latitudinal variation of umbral intensity has been seen in the KPVT observations; the data do not reveal a critical magnetic field strength for eruption at different latitudes as discussed in Schüssler et al. (1994). If the cyclic behavior of the KPVT observations are interpreted to reflect conditions of the toroidal magnetic flux inside the Sun, it suggests that an amplification phase in addition to a decay phase is present in each solar cycle. One recent suggestion for an amplification of the toroidal field, is the conversion of potential energy as described in Rempel & Schüssler (2001). The KPVT umbral intensity measurements, especially combined with the magnetic field changes seen by Penn & Livingston (2006) provide an important constraint for future models of these processes.

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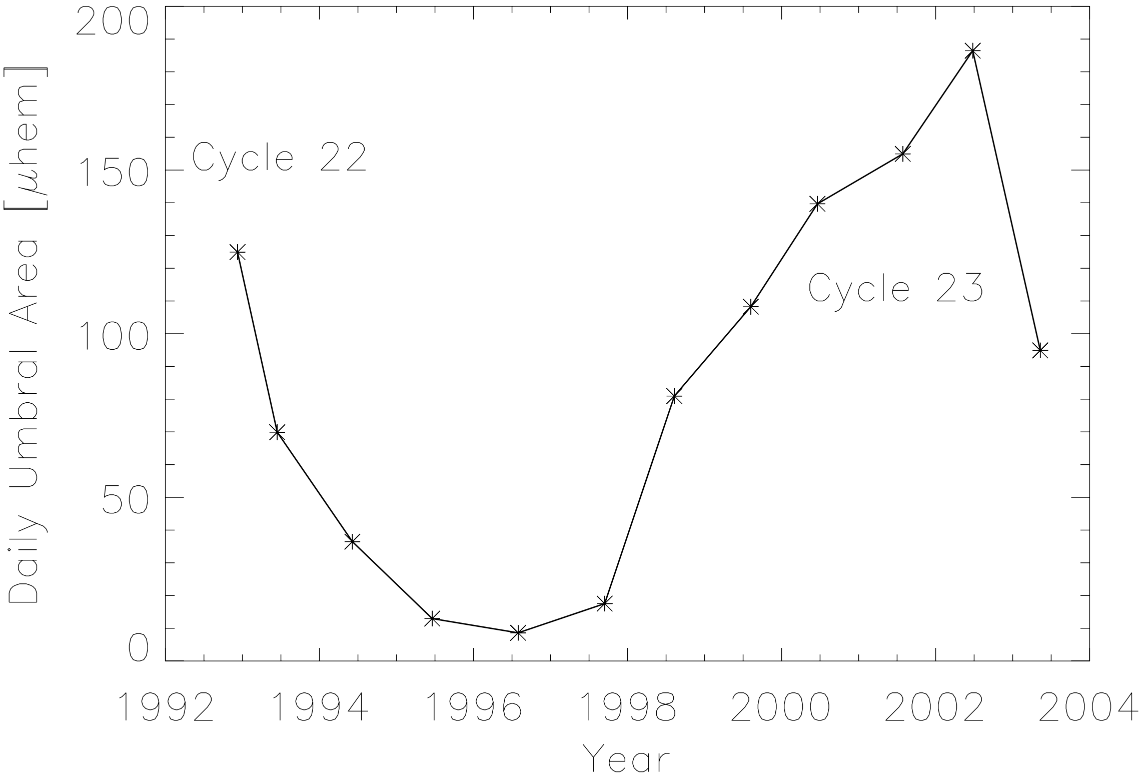

Fig. 1.— The daily umbral area as measured with the KPVT data. The figure shows the well-known sunspot cycle as the data sample a time period from just after the maximum of Cycle 22 to just after the maximum of Cycle 23. The values for the umbral area at the maximum of Cycle 23 are in agreement with those of Cycles 17 and 20 as expected from the work of Howard, Gilman & Gilman (1984)

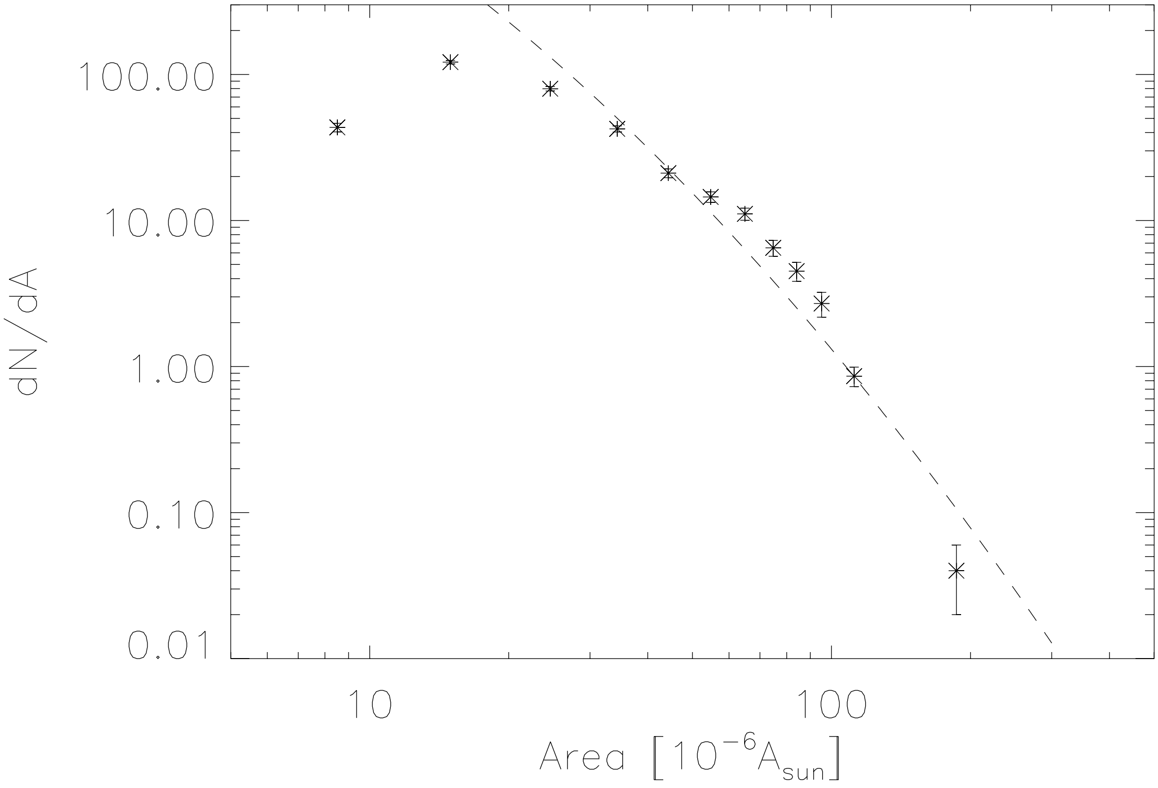

Fig. 2.— The observed distribution of umbral sizes in the entire KPVT data set compared with the log-normal fit function from Bogdan et al. (1988). The KPVT data under sample sunspots in the smallest bin size, probably since only spots with visible penumbra were selected from the images. Excluding these smallest umbrae does not alter the observed long-term umbral intensity time variation.

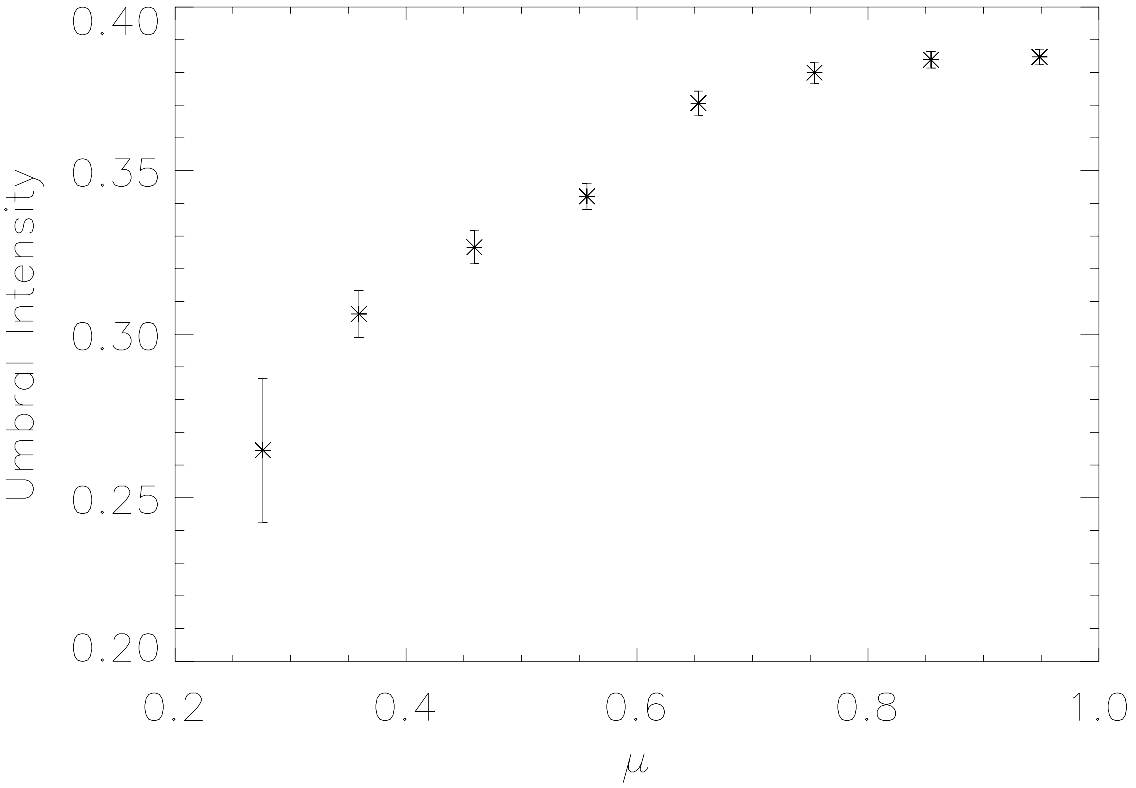

Fig. 3.— The variation of the KPVT umbral minimum intensity with μ, the observed distance from disk center. The decrease of intensity with μ roughly follows that described in umbral models of Maltby et al. (1986) at this wavelength. To avoid making correction for this decrease, only umbrae measured with $\mu > 0.65$ are used for the study of intensity changes with time.

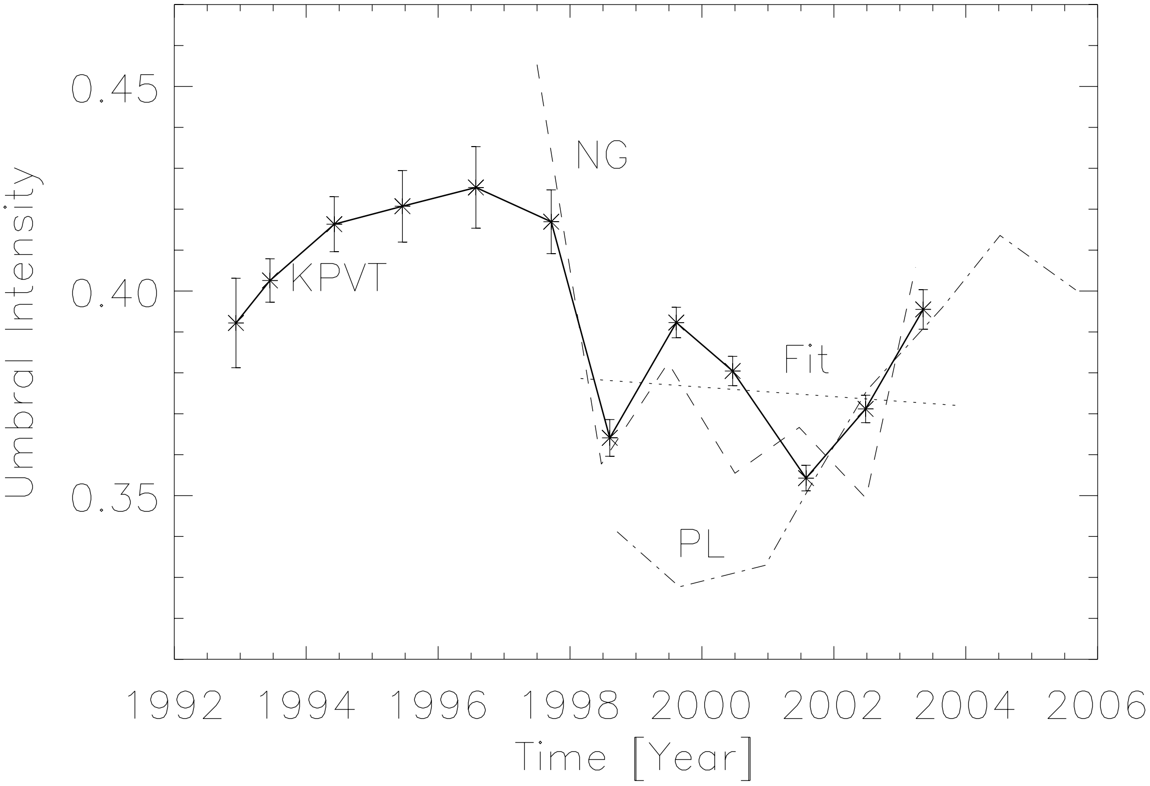

Fig. 4.— Annual average umbral intensity as a function of time from the KPVT data; the error bars represent the standard error of the mean for each annual bin. Sunspot umbrae appear brighter on average during the minimum of the sunspot cycle and darker during the maximum. Shown for comparison are scaled data from Norton & Gilman (2004) (dashed line labeled NG) and Penn & Livingston (2006) (dash-dotted line labeled PL). Also shown is a simple linear fit to all the spot intensities from 1998 March through 2003 October (dotted line labeled Fit) which is in agreement with the results of Mathew et al. (2007).