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II. Spots and Intense Flux Tubes

(J.C. Henoux)

The development of research on starspots, stellar activity, and the suspected relationship between coronal heating and magnetic field have reenforced the interest of the study of the solar magnetic field and the study of the associated thermodynamic

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structures. Several proceedings of scientific meetings appeared from 1984 to 1987 (Measurements of Solar Vector Magnetic Fields, 1985 (I) ; The Hydrodynamics of the Sun, 1984 (II) ; High Resolution in Solar Physics, 1985 (III) ; Theoritical Problems in High Resolution Solar Physics, 1985 (IV) ; Small Scale Magnetic Flux Concentration in the Solar Atmosphere, 1986 (V)). The finding that the solar irradiance in affected by solar activity has renewed interest in photometry of sunspots and faculae. Sunspots have been used for investigating solar differential and meridional motions. Some results are also found in Section III.

A. MAGNETIC FIELDS IN SUNSPOTS AND CONCENTRATED FLUX TUBES

Vector magnetic field measurements are required to determine the strains imposed on the magnetic field of active regions (Parker 1985). Techniques for measurements of vector magnetic fields are reviewed in Measurements of Solar Magnetic Fields (Hagyard, ed., 1985). The Stokes profiles are affected by magneto optic, damping, parasitic light and solar velocity field (Landolfi et al., 1984 ; Landi Degl'Innocenti, 1985 ; Stenflo, 1985a). Numerical methods for solving the radiative transfer equations in the presence of velocity gradients have been published by Skumanich et al. (1985) and Rachkowsky (1986). Makita (1986a), Ye and Jin (1986) investigated Faraday rotation in sunspots. New observations of broad band circular polarization in sunspots were made by Henson and Kemp (1984) and Makita and Ohki (1986). To explain these observations Makita (1986b) assumed a right handed differentially twisted magnetic field. From transverse magnetic field measurements, electric current densities were inferred by Ding et al. (1985), Hagyard et al. (1985), Gopasyuk et al. (1985) and Gary et al. (1987). Isotropic, Pederson, Hall and Cowling photospheric conductivities were computed by Kubat and Karlicky (1986).

The diagnostic foundation for the determination of the magnetic field of unresolved structures was reviewed by Stenflo (1986a,b) and Semel (1986). From the recording of polarized line profiles with high spectral resolution and signal to noise ratio over large portions of the solar spectrum, the KG field strengths, at photospheric level, in plages and network were confirmed (Stenflo, 1984, 1985b ; Stenflo et al. 1984 ; Solanki and Stenflo, 1984).Consistent with the observed center to limb variation of the field strength, the magnetic field strength inferred from the infra-red 1.56 Å line, is larger than that found from lines formed higher in the photosphere (Stenflo et al. 1987a,b). The thermodynamic properties of flux tubes presented in papers listed in B, were derived assuming a tubular geometry. Pneuman et al. (1985) used an expansion technique to take into account the effect of field line curvature. Pizzo (1986) solved numerically the magnetostatic equations for thick flux tubes, and showed that vertical flux tubes of small horizontal scale might have highly divergent magnetic topologies. A review on the theoritical modeling of solar magnetic structures was given by Low (1985), and the causes of magnetic structuring were discussed by Roberts (1984). At the top of a flux tube, the magnetic field lines are concave towards the external gas and therefore liable to the interchange instability. Schussler (1984) showed that a whirl can stabilize the tube.

B. THERMODYNAMIC MODELS OF SUNSPOTS AND CONCENTRATED FLUX TUBES, AND MOTIONS

Moore and Rabin (1985) reviewed sunspots properties. Assuming that sunspots temperatures and densities are independant of sunspots ages, sizes, and types, new reference sunspot models have been published (Staude et al., 1984 ; Yun and Beed, 1986). Three semi-empirical photospheric sunspot models corresponding to the early, middle and late phases of the solar cycle were derived by Maltby et al. (1986), from continuum intensity observations, from 1968 to 1984. On the other hand, on the basis of line observations, Sobotka (1985a,b) proposed 12 semi-empirical models of sunspots of different sizes and ages. The contribution of molecules to the opacity, in the infra-red, and the centre to limb variation of the rotational temperature of SIO fundamental band, for various models, were computed by Punetha and Joshi (1984a,b). The brightness in the continuum is not uniform in umbrae. However Wiehr (1985a) could not explain the variations of brightness with solar cycle by the influence of umbral dots. The size, temperature and half-life time of umbral dats were measured respectively by Grossmann-Doerth et al. (1986) and by Kusoffsky and Lundstedt (1986). Knobloch and Weiss (1984) estimated the periods of non linear convective oscillations that could look like umbral dots. Similar interpretation was made by Choudhuri (1986) in his numerical study of the dynamic of magnetically trapped fluids. On the other hand Kitai (1986) found that umbral dots extend to chromosphere and suggested that they are excited by infalling matter from corona. The average temperature increase in plage and network flux tubes was derived, by Solanki and Stenflo (1985), from a statistical analysis of Stokes I and V line profiles.

Motions are present in magnetic flux tubes. The strong asymmetry of the stokes V profiles implies the existence of line of sight gradients of the velocity in flux tubes. Systematic downflows could explain stockes V profiles observations with moderate field strength (Ribes et al. 1985a,b). Downflows could also provide an efficient mechanism for heating flux tubes by entropy transport (Hasan and Schussler, 1985). On one hand large stokes V zero crossing wavelength shifts were reported by Wiehr (1985b) and Scholiers and Wiehr (1985). On the other hand no Doppler shift of the stokes V zero crossing position greater than 200 m s^{-1} was observed on high resolution polarized spectra (Solanki, 1986). Cavallini et al. (1985, 1987) interpreted observed asymmetries and shifts as due to convection weakening in flux tubes. By convoluting spectrally resolved stokes V profiles with various model instrumental profiles, Solanki and Stenflo (1986) concluded that the published V zero crossing wavelength shifts are consistent with the absence of steady downflows during their 30 minutes integration time. Then they explained the large asymmetries, large non-thermal broadenings, and small Doppler shifts by oscillations. Oscillations in flux tubes might be produced by convective instability (Hasan 1984, 1985) or might be resonant oscillations induced by external pressure fluctuations (Venkatakrishnan 1986).

Recent observational and theoritical work on oscillations in sunspots has been reviewed by Thomas (1985). Photoelectric observations of chromospheric sunspot oscillations were reported by Lites (1985). Lites and Thomas (1985) interpreted the observed 3 minutes oscillations as a resonant mode of fast magnetoatmospheric waves in the sunspot photosphere. At the same time Staude et al. (1985) explained the oscillations observed, on the SMM spacecraft, in transition zone lines, as a resonant mode of slow magnetoatmospheric waves above the temperature minimum region. Similar explanation was used by Lites (1986a,b) who suggested non linear interaction between the two kinds of waves. Further evidence for the resonant chromosphere model were reported by Gurman (1987) and Thomas et al. (1987). New observations of the interaction of solar modes with a sunspot were reported by Abdelatif and al. (1986). The steady-state characteristics of the Evershed flow as been investigated, in the photosphere by Makita an Kawakami (1986), Kuveler and Wiehr (1985), Wiehr et al. (1986) and Wiehr and Stellmacher (1985), and in both photosphere and chromosphere by Dialetis et al. (1985). Long period (45 minutes) photospheric velocity oscillations were observed by Gopasyuk (1985) and by Berton and Rayrole (1985) who also observed associated magnetic field torsional oscillations. The correlation between flare activity and sunspot rotation was confirmed by Gopasyuk and Lazareva (1986).

C. ORIGIN AND DECAY OF SUNSPOTS AND CONCENTRATED FLUX TUBES

A widely used working hypothesis in the investigation of sunspot formation is the emergence of intense magnetic flux tubes from beneath the photosphere. Zwaan (1985a,b) and Garcia de la Rosa (1984) explained sunspots appearance by the emergence of a loop shaped bundle of many flux tubes. Interaction of these flux tubes with giant cells and supergranules is suggested by Mc Intosh and Wilson (1985). Monero-Insertis (1984) confirmed the imposibility of keeping toroidal flux tubes in the deep convection zone for any time longer than a small fraction of the solar cycle period. Following Schussler (1984) the bottom of the convective zone is a favorable region for magnetic field concentration. Giovanelli (1985) revisited the interaction of flux tubes with the convection zone pointing out the importance of the potential energy and of the gas entry in the tube. The cooling time scales of growing sunspots were investigated by Chou (1987). New observations of submergence of magnetic field without spreading or diffusion were reported (Rabin et al., 1984 ; Zirin, 1985), suggesting that the magnetic field is help by subsurface forces (Parker, 1984). On the other hand De Vore et al. (1985) and Sheeley et al. (1986) simulated the evolution of a sample of magnetic regions and of the gross solar magnetic field, by solving a transport equation at the photosphere and Grossmann-Doerth et al. (1987) suggested a spurious variation of photospheric magnetic flux. 3 D numerical simulations of the effect of convection on buoyant magnetic flux tubes (Nordlund, 1985 ; Schmidt et al., 1985 ; Weiss, 1985) lead to qualitative agreement with observations that small flux tubes are swept to the cell boundary, while larger are dragged to the axis of the cell. Mechanism of generation of magnetic fields in photospheric layers have been reviewed (Wilson, 1986). The idea that cyclonic motions, in large scale magnetic field patterns, are at the origin of sunspots was reexamined : Akasofu (1984a,b, 1985) qualitative model of sunspot cyclonic origin is based on the photospheric ambipolar dynamo effect that is also invoked by Simon and Wilson (1985) to explain 20-40 minutes flux changes in small magnetic regions ; Schatten and Mayr (1985) reconsidered sunspot cooling by superadiabatic effect in the presence of cyclonic motions. A statical study of the spiral spots was made by Ding et al. (1987). The apparent E.W. asymmetry of appearance and disappearance of short lived sunspot groups was explained by Kopecky (1985). The distribution Density Function of sunspot groups as a function of lifetime was determined by Kuklin (1985). A quasi-biennal oscillation in sunspot activity, over the period 1749-1981, was found by Apostolov (1985), and Wilson (1986) reported an even-odd cycle distribution in Mt. Wilson number of spots data. Castenmiller et al. (1986) investigated the properties of the Gaizauskas type of complex of activity.

D. SUNSPOT MOTIONS

No clear picture comes out yet of the published results of investigations on sunspot velocity. Sunspot velocity depends of age (Gokhale and Hiremath, 1984) and type. Differential rotation occurs between sunspots within a group (Gilman and Howard, 1986). From the observed correlation between longitude and latitude motions, Gilman and Howard (1984, 1985) concluded that angular momentum might be transported towards the equator by sunspots. Results on meridional circulation are still controversial. A general drift towards south for spots in the equator near regions was found by Hanslmeier and Lustig (1986) and Lustig and Hanslmeier (1987). Other authors observed an average midlatitude northward flow (Howard and Gilman, 1986) or did not find any meridional motion significantly different from zero (Balthasar et al. 1986). Restraining their investigation to young sunspots, Ribes et al. (1985c) found four latitude bands with alternate direction of circulation that reverse during the solar cycle. Tuominen and Vitanen (1984) related the meridional flow to the cycle and to torsional oscillations.

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