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HEATING OF THE STELLAR CORONA

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INTRODUCTION

Coronal heating is the general cause of stellar X-ray emission, and it is also the cause of stellar mass loss in most stars. Hence a quantitative theory of coronal heating is an essential part of X-ray astronomy, and the development of a correct theory of coronal heating should be a primary concern of X-ray astronomers. The magnetohydrodynamical effects involved in coronal heating are not without interest in their own right, representing phenomena largely unknown in the terrestrial laboratory. Until these effects can be evaluated and assembled into a comprehensive theory of coronal heating for at least one star, the interpretation of the X-ray emissions of all stars is a phenomenological study at best, based on arbitrary organization and display of X-ray luminosity against bolometric luminosity, rotation rate, etc. The sun provides the one opportunity to pursue the exotic physical effects that combine to heat a stellar corona.

The hard work that has gone into studying the solar atmosphere and the solar photosphere over the past fifty years has finally, with the aid of modern technology, begun to get hold of the essential physical effects that cause the corona. A variety of theoretical effects have been proposed, many have been explored in some detail, and it is the purpose of this review to summarize the present state of development of the theory of coronal heating. The reader is also referred to other articles in these Proceedings which present quite recent results on additional effects not elaborated here.

To review the theoretical building blocks for coronal heating, the corona of the sun may be divided into two distinct states, representing qualitative differences in the magnetic field configuration. The active X-ray coronal regions are contained within strong closed (re-entrant) magnetic fields arching up from the surface of the sun (Vaiana, Krieger and Timothy, 1973). In contrast there are the coronal holes of low gas density to be found in regions of weak open field extending to infinity in the escaping solar wind (Altschuler, et al. 1972, Hundhausen, 1972; Krieger, Timothy and Roelof, 1973). There is, too, the so called 'quiet corona' to be found on the peripheries of the active regions and coronal holes. It is not entirely clear whether the quiet corona is best thought of as a weak form of active corona, or a nonexpanding coronal hole - probably the former.

The active corona and the coronal hole represent distinct coronal states that have little in common besides their high temperatures. The typical magnetic field strength in the active corona is of the order of 10^2 gauss, as opposed to 10 gauss in a coronal hole. The number density N in the active corona may be as high as 10^{10} atoms/cm^3, as opposed to N = 10^8 atoms/cm^3 in the coronal hole. It follows immediately that the active corona is the principal source of X-rays, while the coronal holes emit relatively little - so little that they appear as blank regions in an X-ray photograph, from which they derive their name 'coronal hole.' The active X-ray corona has temperatures typically 2-3x10^6 K, with a sound speed of 250 km/sec, while a coronal hole has a temperature of 1.5-2x10^6 K and a sound speed of 200 km/sec (See Billings 1966; Kohl, et al. 1980, 1984; Withbroe et al. 1982a,b; Withbroe et al. 1985). The Alfven speed V_A is about the same in both regions, of the order of 2000 km/sec, the lower field strength in the coronal hole compensated by the much lower gas density. The heat input is estimated (Withbroe and Noyes, 1977) to be I = 10^7 ergs/cm^2 sec to maintain the active corona, most of which is emitted as UV and X-rays. The heat input to coronal holes is of the order of I = 10^6 ergs/cm^2 sec, with most of it going into the expansion of the gas to produce the solar wind (Withbroe and Noyes, 1977). One of the more astonishing features of the active corona - beyond the fact that nature produces such a thing in the first place - is that the surface brightness of the active regions is approximately independent of the dimensions, from the small ephemeral active region with a characteristic scale L = 10^4 km to the large normal active region with a characteristic scale L = 10^5 km or more. Detailed studies of the active corona have shown that there is a close and detailed association between magnetic field strength B and heat input I (Rosner, Tucker and Vaiana, 1978; Golub et al. 1980). This immediately suggests the possibility that the active corona is heated by hydromagnetic waves, which propagate more copiously into the corona where the magnetic field is strongest. We examine this possibility first before considering the alternatives.

This is perhaps the appropriate place to note the extreme dynamical state of the solar corona. It is an atmosphere that would collapse in a matter of an hour if the heat supply were turned off. For instance, in the active corona the enthalpy density $\mathcal{E}$ = 5 NkT is about 14 ergs/cm^3, with a characteristic pressure scale height $\Lambda = kT/\mu Mg = 10^{10}$ cm and a total thermal content, therefore, of the order of $\Lambda\mathcal{E} = 1.4\times10^{11}$ ergs/cm^2. The characteristic heating (and cooling) time $\tau = \Lambda\mathcal{E}/I$ is then 1.4x10^4 sec, or about four hours. The thermal capacity of the coronal hole is about a hundredth as great, so that the characteristic heating time is 1.4x10^3 sec, or 24 minutes! Hence the corona is sustained hour by hour by its heat source. The characteristic pass-through rate is enormous, with Λ/τ=7 km/sec in the active corona and 70 km/sec in the coronal hole.

WAVE HEATING IN THE ACTIVE CORONA

Consider how energy may be transported from the convective zone and deposited in the active corona by Alfven waves, with all other modes dissipated in the chromosphere or refracted away from the vertical before reaching the corona (Leer, Holzer, and Fla, 1982; Hollweg, 1984). The interesting observational fact is that no Alfven waves have been identified so far. The search for waves has produced only an upper limit on the rms fluid velocity $\langle v^2\rangle^{1/2}$ in the line of sight based on the observed line widths and the expected thermal velocities. In the active corona the rms velocity in the line of sight is $\langle v^2\rangle^{1/2} < 20$ km/sec (Beckers, 1976, 1978; Beckers and Schneeburger, 1977; Bruner, 1978, Cheng, Doschek and Feldman, 1979). At r = 1.2 $R_\odot$ in coronal holes the limit is apparently not much different (cf. Esser, et al, 1986). The maximum energy flux is $F=2\rho\langle v^2\rangle V_A$, achieved when all the waves are propagating in the same direction (presumably outward) along the magnetic field. The factor of two takes account of the two states of transverse polarization. With the numbers already quoted, then, the upper limit on F is 2.6x10^7 ergs/cm^2 sec. This is comfortably above the require heat input of $I = 10^7$ ergs/cm^2 sec, until we come to the next question, viz. the dissipation of the waves.

Almost half of the upper limit F of the upward propagating waves must be dissipated to heat the active corona. But if half is dissipated, then half is not dissipated, and the surviving waves propagate around the magnetic field and down the other side where they contribute to the $\langle v^2\rangle^{1/2}$ without contributing to the upward transport of energy. It is immediately obvious, then, that something over half of the wave energy must be dissipated in one pass around the arched magnetic field of the active corona. Roughly, the wave energy must decline by a factor of, say, four, so that the amplitude is down by half (Parker, 1983b, 1985a).

Oscillations at the surface of the sun are observed with periods of 100 sec, giving a wavelength of $2x10^5$ km in the corona, where $V_A = 2x10^3$ km/sec. The lengths of the lines of force above a normal active region are comparable to this wavelength, from which it follows that the wave must damp strongly in about one wavelength. Recalling that the same energy goes into an ephermeral active region with one tenth the dimensions, we are forced to postulate waves with periods of 10 sec, which damp equally effectively in one pass around the arched field of the ephemeral region. It is customary to make the best possible case for wave heating by assuming that $\langle v^2\rangle^{1\ 2}$ is equal to the observational upper limit of about 20 km/sec. Note, then, that the requirement of damping Alfven waves in approximately one wavelength cannot be accomplished by any conventional means. The waves are of small amplitude with $\Delta B/B = \langle v^2\rangle^{1/2}/V_A = 10^{-2}$, so that nonlinear effects are negligible. Electron conduction velocities are of the order of a few km/sec at most, so that no anomalous resistivity is expected. Phase mixing has insufficient time to develop.

Hollweg (1984, 1986) has pointed out that the necessary conditions for dissipation are reminiscent of the breakup and dissipation of the eddies in classical hydrodynamic turbulence. Eddies with scale l and characteristic velocity v are broken up into smaller eddies in a time of the order of l/v. If we imagine then that the flux tubes (each attached to a separate fibril) oscillate independently where they are packed together in the corona, then there are velocity discontinuities between contiguous flux tubes. Such intense oscillating shears may be unstable, producing turbulence which cascades to smaller wavelengths and has the basic characteristics of classical turbulence. Hollweg refers to this theoretical possibility as the 'Kolmogoroff hypothesis' for the necessary dissipation to heat the active corona with waves. One needs, in addition to the 'Kolmogoroff hypothesis' a wave input spectrum at the photosphere extending with sufficient power to high frequencies (period of 10 sec or less). Very approximately, rms velocities of 0.4 km/sec are needed in each frequency interval. Indeed a very crude estimate can be made of the <u>lower</u> limit on the velocity amplitude in the photosphere necessary to produce a wave of given amplitude in the corona. The estimate is based on the fact that the amplitude of an Alfven wave varies as $\rho^{-1/4}$ while propagating along a slowly varying magnetic field B in an infinitely conducting g as with slowly varying density ρ. If either ρ or B varies rapidly, there are reflections which reduce the transmitted waves. One could argue that resonances between reflection points might allow an accumulation of amplitude but that seems to be excluded in the present case by the necessary heavy damping. So it appears that $v \propto \rho^{-1/4}$ should give an upper limit to the wave amplitude in the corona for a given amplitude in the photosphere. The number density in the photosphere is of the order of 10^{17} atoms/cm^3 and 10^{10} atoms/cm^3 in the active corona, so $\rho^{1/4}$ varies by about a factor of 50. Hence, an rms wave velocity of 20 km/sec in the corona requires an rms wave velocity of at least 0.4 km/sec in the photosphere in whatever frequency interval is appropriate for the scale (10^4–10^5 km) of the active region under consideration. And of course the inappropriate frequencies must <u>not</u> contribute much to the rms velocity in the active region or there cannot be enough energy transport within the overall observational upper limit of 20 km/sec. Hollweg estimates an rms photospheric velocity of about 1.2 km/sec over the entire range of frequencies would suffice. This translates into 60 km/sec in the corona unless one can think of a reason to exclude the frequencies inappropriate for heating the particular active region in mind.

TOPOLOGICAL DISSIPATION IN THE ACTIVE CORONA

There is a theoretical alternative to wave dissipation for heating the active corona, and that is the so called 'nonequilibrium' of a magnetic field in a highly conducting fluid when the footpoints of the field (at the boundary) are shuffled among each other in some random fashion, thereby randomly winding and wrapping the lines of force about each other in the corona above. It has come to be realized over the past two decades that the magnetostatic equilibrium of such fields involves internal tangential discontinuities, i.e. current sheets with the field direction changing by a finite amount across each discontinuity. The field is then in static equilibrium everywhere between the surfaces of discontinuity (Parker, 1972, 1979 pp. 359–391, 1981a,b, 1982, 1983a,b,c,d, 1985b, 1986; Yu, 1973; Tsinganos, 1982; Tsinganos, Distler and Rosner, 1984; Moffatt, 1985, 1986; Vainshtein and Parker, 1986 and references therein. Van Ballegooijen, 1985 maintains that discontinuities do not form).

There is a discontinuity in the direction of the field only in the limit of infinite electrical conductivity, of course. In any real situation, involving finite conductivity, finite ion cycloton radius, etc. the 'discontinuity' has a finite thickness and the fluid within the finite thickness has no static equilibrium. The situation is the familiar neutral point nonequilibrium configuration in which the fluid is squeezed (by the pressure of the field on either side) away from the neutral point in the transverse component of the field (see discussion and sketches in Parker, 1979, pp. 392–439. See applications and references in Priest, 1981, 1982; Van Hoven, 1981; Parker, 1983d).

The point of interest for heating the active corona is that the neutral point nonequilibrium produces a current sheet that constantly grows thinner and more concentrated as the fluid squeezes out from between the opposite transverse fields on either side, so there is rapid dissipation no matter how small the electrical resistivity. As a matter of fact, the high electron conduction velocities within the current sheet may produce plasma turbulence and anomalous resistivity (cf. Drake, 1984 and references therein) and one expects the resistive tearing mode instabilities (cf. Steinolfson and Van Hoven, 1984; Horton, Tajima and Galvao, 1984 and references therein).

Suppose, then, that the turbulent convection beneath the photosphere causes the individual magnetic fibrils to wander at random among each other, taking steps of length λ at a velocity v. To keep the picture simple, suppose that λ is at least as large as the mean separation of independent fibrils. The magnetic flux tube extending up from each fibril becomes entwined among all the other tubes in complicated ways as the individual fibril wanders through the 'forest' composed of all the others. The pathlength traversed by any one fibril after a time t is vt. Consider the simple situation where the lines of force are initially vertical and the far ends are fixed in a plane at a height L above the footpoints. It follows that the average line of force is deflected from the vertical by an angle θ, where $\tan\theta = vt/L$, after a time t. If the mean vertical field has an intensity B, the horizontal component is $B_\perp = B \tan\theta$. The inclined field trailing out behind the individual fibril pulls back on the fibril as the fibril wanders in and out among its neighbors. The mean force is $BB_\perp/4\pi$ dynes/cm², so that the rate at which the motion v does work on the field is (Parker, 1983b)

$$W = v\, BB_\perp /4\pi$$

$$= (B^2/4\pi)\, v^2 t/L \ \text{ergs/cm}^2\ \text{sec}$$

If we imagine that the random walk of the fibrils has a characteristic velocity v of 0.5 km/sec in an active region where $B = 10^2$ gauss, the energy requirement $W = 10^7$ ergs/cm² sec yields $B_\perp = 25$ gauss. That is to say, $B_\perp = B/4$ and $vt=L/4$. The lines of force are inclined on the average about 14° from the vertical. With $L=10^5$ km for a normal active region a time $t=5\times10^4$ sec (14 hours) is required to accumulate this degree of wrapping. The same state is reached in the ephemeral active region ($L=10^4$ km) in about 1.4 hours. We suggest, that the neutral point reconnection, which is the principal (nonlinear) dissipation mechanism at the current sheets, becomes strong at this level of wrapping and destroys the current sheets as fast as they are created. Note that if the dissipation is <u>less</u> effective, the wrapping accumulates to higher levels and the energy input is <u>greater</u>.

HEATING CORONAL HOLES

The coronal hole, with its open magnetic field extending to 'infinity', presents quite a different problem from the active corona. There can be no significant wrapping and winding of the magnetic lines of force because the winding is propagated away to infinity at the Alfven speed of 2000 km/sec. The only known mechanism for supplying the necessary 10^6 ergs/cm² sec (Withbroe and Noyes 1977) is Alfven waves, with an rms velocity $\langle v^2\rangle^{1/2}$ of about 35 km/sec in each direction transverse to the field B = 10 gauss. Using the simple relation that the wave amplitude varies as $\rho^{-1/4}$ during propagation from the photosphere into the corona, we find that $\rho^{-1/4}$ increases by a factor of 1.5×10^2, so that $\langle v^2\rangle^{1/2} = 35$ km/sec in the corona is associated with transverse motions of the order of 1/4 km/sec at the photospheric level.

The damping of Alfven waves in a coronal hole is presumably a leisurely affair, occurring over distances of many solar radii. Waves with a period of 100 sec have wavelength $\lambda=2\times10^5$ km, so that $10R_\odot$ (7×10^6 km) is equivalent to 35λ. Phase mixing increases the characteristc gradients in the wave to large values, and one may reasonably expect that a major portion of the wave energy is converted into heat (see discussion in Haeyverts and Priest, 1983; Nocera, Leroy, and Priest, 1984). Any wave motion that is not dissipated propagates out into the solar wind, where one sees Alfven waves of large amplitude (Parker, 1965, 1966; Hundhausen, 1972; Terasawa et al. 1986; Hollweg, 1986 and references therein).

The acceleration of the solar wind in its relation to hydromagnetic wave transport of both energy and momentum has been treated by Leer, Holzer and Fla (1982). The structure of the coronal hole has been studied with rocket observations of EUV (Orrall, Rottman, and Klimchuck, 1983 and references therein), and of Lα out to about 4RO (cf. Withbroe et al., 1982a,b, 1985; Esser et al., 1986) providing estimates of the kinetic temperature, the coronal expansion velocity and the residual $\langle v^2 \rangle^{1/2}$ that might be attributed to Alfven waves (see also Hollweg, et al., 1982). On the basis of these works it appears that coronal holes are heated primarily by the dissipation of Alfven waves introduced into the magnetic field by the granule motions at the photosphere. It is Alfven waves, then, that supply the thermal energy that drives the solar wind and creates the heliosphere. The Alfven waves that survive the dissipation to reach r = 4RO contribute their momentum to the solar wind, boosting the velocity of the high speed streams above that available from thermal expansion alone.

DISCUSSION

It is evident from the foregoing discussion that heating the active coronal regions presents a formidable theoretical problem. The observational upper limit of about 20 km/sec on the rms velocity in the active corona seriously constrains the theoretical options. Noting that $\langle v^2 \rangle^{1/2}$ = 15 km/sec is required to carry in the necessary 10^7 ergs/cm^2 sec, there is little room left for reflected waves, etc. The damping must occur on the first pass around the coronal arch (see Hollweg, 1986). We are inclined to the view that the Alfven waves are the primary source of energy input to the coronal hole, whereas in the active corona they contribute relatively little to the heating, with most of the heat input from the current sheets formed by the random walk of the footpoints of the field at the photosphere. The general occurrence of high speed micro-jets in the transition region shown by Deubner (these Proceedings) suggests neutral point reconnection at many small tangential discontinuities in the magnetic field throughout the active corona. But we do not feel that the issue is settled at this point in time. There are still too many unknown quantities. None of the theoretical ideas for heating either the active corona or the coronal holes is anything more than a sophisticated conjecture until additional theoretical possibilities have been explored and until observations establish the nature of the agitation of the field at the photosphere, and, hopefully, in the corona.

On the theoretical side, we should be aware that the coronal heating produced by spicules, and, indeed, the origin of the spicules has not been fully determined (see R. Kopp, these Proceedings). Hollweg's Kolmogoroff hypothesis needs careful consideration (see A. Van Ballegooijen, these Proceedings). The idea that there is strong wave resonance and intense dissipation in layers so thin as to escape observation (see Davila, these Proceedings) needs a careful evaluation, with particular attention to the strength of the waves within the resonant cavity compared to the waves presumed to drive the resonance by penetrating into the cavity from the outside. The question is, then, whether the scheme can be made to supply the 10^7 ergs/cm^2 sec without violating the observational upper limit of 20 km/sec.

A recent paper by Lee and Roberts (1986) explores the local transverse oscillations produced by the passage of Alfven waves past a tangential discontinuity in the Alfven speed V_A ($B \times \nabla V_A \neq 0$). Their calculations illustrate the possibilities for dissipation that may occur when Alfven waves propagate along a field containing a number of tangential discontinuities in the field direction.

That is to say, the combination of waves plus discontinuities opens up the possibility of a wave contribution to heating the active corona that has not yet been properly assessed.

On the observational side, it is essential to determine the diameter, field strength, and internal structure of the individual magnetic fibrils at the photospheric level, and to determine the spacing and grouping of the individual fibrils, and their location in the granule and supergranule motions. Then, the individual and collective motions of the individual fibrils must be determined to show the form of the field distortions to be expected in the corona. In particular, the Fourier spectrum $F(\omega)$ and the random walk $F(0)$ of the individual fibrils in both active and quiet regions are essential input data, presently missing. We are all inclined to assume fibril motions of the order of 0.5 km/sec at our favorite frequency to evaluate the potential of various schemes for coronal heating. Sooner or later this 'not unreasonable' practice must be replaced by hard information from high resolution (0.1'') observations of the surface of the sun. An instrument comparable in performance to the late lamented SOT is an essential step in establishing the causes of the corona of the sun. And until that goal is achieved, stellar X-ray astronomy is mired in phenomenology, unable to advance to hard scientific interpretation.

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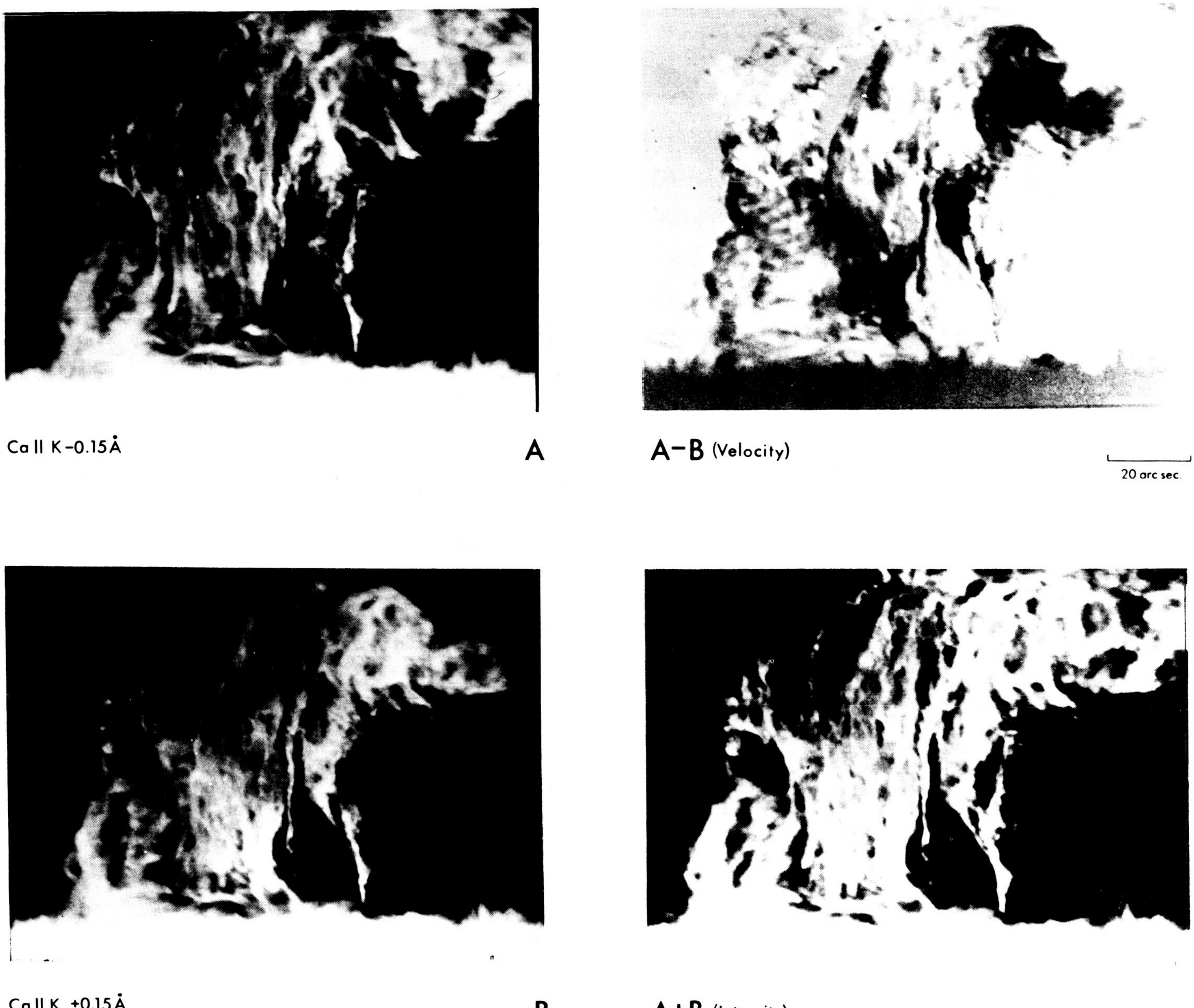
PROMINENCES

Prominence · February 22, 1974

PA(H)=128°



Intensity and velocity of Prominences observed at Sac Peak Solar Observatory.

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