Probing the Sun's hot atmosphere

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The solar corona is an extremely hot (10^6 K), almost fully ionized plasma which extends from a few thousand km above the photosphere to where it freely expands into the solar system as the solar wind. The exact reason for its high temperature is still unknown, despite more than 50 years of research, but magnetic fields are certainly involved. This article reviews some recent progress in our understanding using data from spacecraft (*SOHO*, *Yohkoh*, and TRACE) as well as ground-based eclipse experiments.

1. History of coronal studies

Against the expectations of the Second Law of Thermodynamics, the outer atmosphere of the Sun is hotter than the visible surface or photosphere, from which much of its radiation is emitted. The chromosphere, that part of the Sun's atmosphere which is up to 900 km above the photosphere, has a temperature which rises from a value of 4400 K, the temperature minimum (a region some 500 km above the photosphere), to temperatures of up to 20,000 K, where the dominant radiation is the Lyman lines of neutral hydrogen. Extending above the chromosphere and into the interplanetary space is the solar corona, an extremely hot, tenuous part of the Sun's atmosphere where the temperature is typically (1 to 2) $\times 10^6$ K, locally much more. Both the chromosphere and corona are highly structured, with clear evidence of association of magnetic fields which are revealed at the photospheric layers by the Zeeman splitting of magnetically sensitive Fraunhofer lines. The coronal structures are generally loops or large arches, with footpoints apparently in the photosphere, but there are also radial structures called streamers which extend out to very large distances. Over the polar regions, almost radial structures known as plumes are present, giving the white-light corona during total eclipses the appearance of a bar magnet's field pattern. This is an important clue to the physical properties of the solar corona.

The corona's high temperature means that it is visible at ultraviolet and X-ray wavelengths, and so many spacecraft and rocket instruments over the years have studied its character. However, it is also visible to the naked eye during the rare circumstances of a total eclipse, when the Moon covers the bright photosphere. The corona then appears as a pearly white, often irregularly shaped, structure all round the Moon's limb (Figure 1). The white-light emission is mostly due to Thomson-scattered photospheric light off fast-moving free electrons in the corona. The spectrum of this radiation – the so-called K corona – has the broad characteristics of the photosphere's spectrum but without the Fraunhofer lines, since they have line profiles which are so highly Doppler-broadened that they cannot be made out against the continuous spectrum. There is a faint extra component, the F corona, due to dust particles in interplanetary space which scatter photospheric radiation also. In this case, the cold dust particles faithfully reproduce the photospheric spectrum including the Fraunhofer lines.

The first clues that the corona might be an unusually hot environment were obtained during total eclipses in the nineteenth century. Astronomers were motivated to go to eclipses, even if they were only visible in remote parts of the Earth, as there was no other means available then of studying the Sun's outer atmosphere. The Americans Young and Harkness studied the corona during the 1869 total eclipse and found a bright emission line at 530.3 nm (to become known as the 'green' line) which was unknown in laboratory spectra[1]. Several more unidentified lines became evident in spectra obtained in subsequent eclipses, and a new element named 'coronium' was suspected to be the reason for these spectral lines. As the years passed, however, the periodic table of elements began to be much better understood and it was clear that coronium (as well as 'nebulium', discovered from spectral lines in certain gaseous nebulae) could not be easily admitted into the scheme. It was not until the 1930s and 1940s were the lines of coronium and nebulium reproduced in the spectra of very hot spark sources in the laboratory, so it was then realized that the corona must have a temperature of at least that in sparks, nearly a million degrees K. The clinching argument was the discovery by Edlén that the green line was due, not to an unknown element, but to 13-times-ionized iron. Edlén's work also led to the identification of other coronal lines as being due to multiply ionized atoms of familiar elements like Fe and Ni (see, Phillips[1] for more details).

2. The spacecraft era

The solar corona is a strong radiator in the ultraviolet and X-ray parts of the spectrum. This radiation is absorbed by

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Figure 1 *a*. Computer-processed image of the total solar eclipse in India on 24 October 1995 (Courtesy E. Hiei).

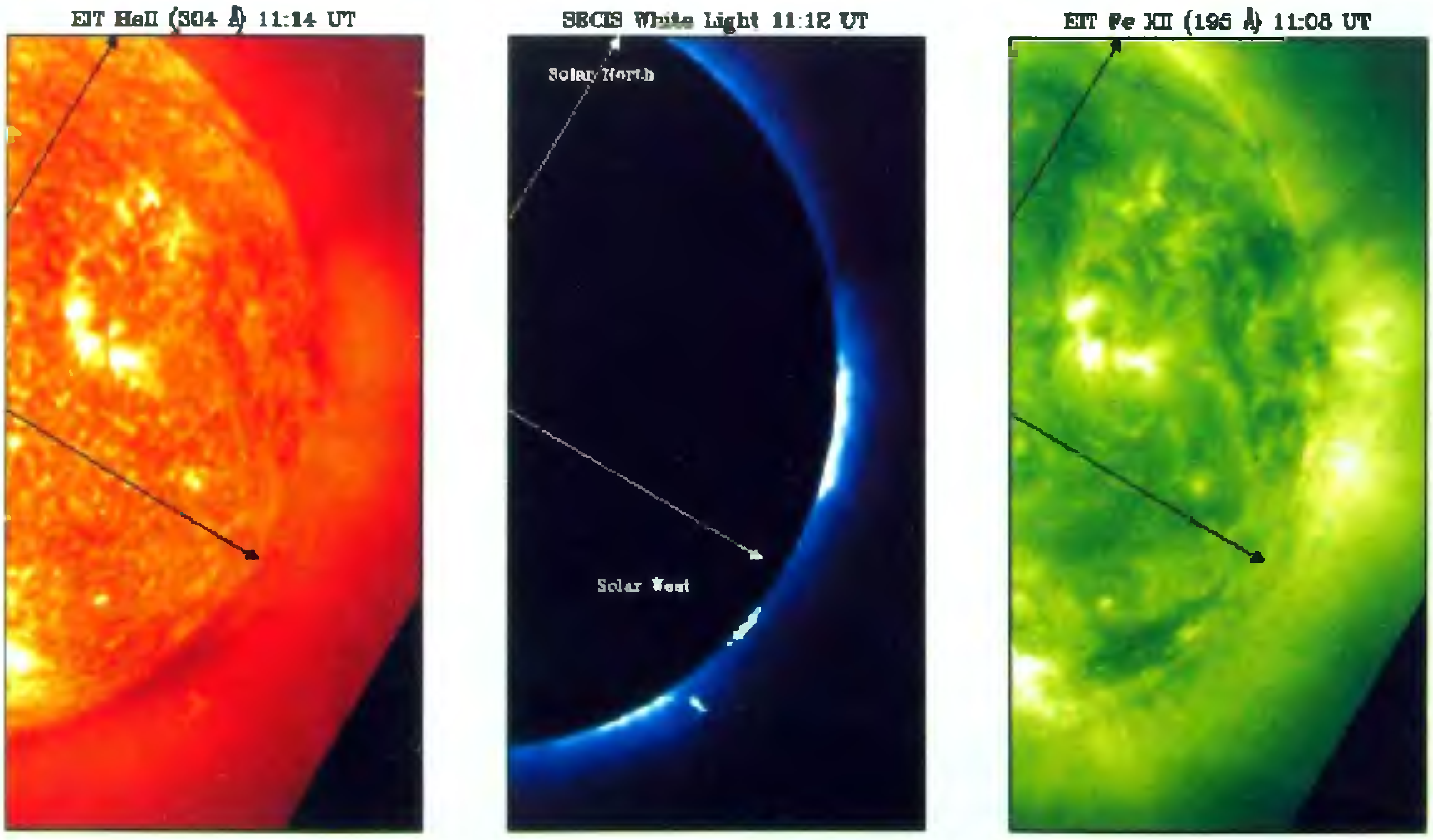

Figure 1 *b*. Images of part of the west limb of the Sun as follows: (*left*) From the EIT instrument on the *SOHO* spacecraft, He II (304 Å) image; (*right*) From the EIT instrument on the *SOHO* spacecraft, Fe XII (195 Å) image; (*centre*) One of 6364 images obtained with the SECIS instrument in Shabla, Bulgaria, during the total solar eclipse of 11 August 1999. Prominences in the SECIS image can be seen in the EIT He II image (emission temp. 20,000 K) while coronal loops above sunspot regions can be seen in the EIT Fe XII image (emission temp. 10^6 K).

the Earth's atmosphere so instrumentation has to be flown on rockets or satellites to be able to view it. Observations were begun shortly after World War II by US groups, notably at the Naval Research Laboratory[1]. Tousey and colleagues obtained the first ultraviolet spectra of the solar atmosphere, finding that the hydrogen Lyman-alpha line, emitted by the chromosphere, was a strong feature at 121.6 nm. Solar X-ray emission was first detected by Burnight in 1949 using a pinhole camera on board a rocket. Spacecraft built by the USA and Soviet Union in the 1960s and 1970s dedicated to solar observations added much to our knowledge of the solar atmosphere, with the manned Skylab Mission of 1973–1974 providing an enormous boost. Ultraviolet and X-ray telescopes on board gave the first high-resolution images of the chromosphere and corona and the intermediate transition region (temperatures between 10^4 and 10^6 K). Images of active regions revealed a complex of loops which varied appreciably over their lifetimes, while ultraviolet images of the quiet Sun showed that the transition region and chromosphere followed the 'network' character previously known from Ca II K-line images. (The Ca K-line is a visible-wavelength line formed in the chromosphere.) The X-ray images showed that the quiet-Sun corona was characterized by diffuse large-scale loops.

In more recent times, the spatial resolution of spacecraft instruments have steadily improved to extremely impressive levels, almost comparable to what can be achieved with ground-based solar telescopes. The Japanese *Yohkoh* spacecraft, launched in 1991, has on board the US/Japanese soft X-ray telescope (SXT), which images X-rays from active and quiet-Sun regions and flares (which are sudden releases of energy in active regions) with a resolution of about 2 arc seconds (1 arc second corresponds to 725 km at mean solar distance: the mean solar diameter is 32 arc minutes). X-rays with wavelengths in the range 0.2–2 nm are sensed by the SXT. *Yohkoh*, which is in a low-Earth orbit, continues to operate at the present time, and has obtained many thousands of images from the SXT (Figure 2) as well as considerable amounts of data from the other instruments on board which are mainly for detecting X-ray emission during flares.

The ESA/NASA Solar and Heliospheric Observatory (*SOHO*) was launched in 1995 into an orbit about the inner Lagrangian (L1) point situated some 1.5×10^6 km from the Earth on the sunward side. Its twelve instruments therefore get an uninterrupted view of the Sun, unlike the instruments on *Yohkoh*. Apart from a period in 1998 when the spacecraft was temporarily out of contact, there have been continuous operations since launch. There are several imaging instruments, sensitive from visible-light wavelengths to the extreme-ultraviolet. The Extreme-ultraviolet Imaging Telescope (EIT), for instance, uses normal-incidence optics to get full-Sun images several times a day in the wavelength bands containing lines emitted by the coronal ions Fe IX/Fe X, Fe XII, Fe XV (emitted in the temperature range 600,000 K to 2,500,000 K) as well as the chromospheric He II 30.4 nm line (Figure 3). The spatial resolution is about 2 arc seconds (1500 km). The set of three coronagraphs making up the Large Angle and Spectrometric Coronagraph (LASCO) view the white-light corona with high resolution out to distances of 30 solar radii (1 solar radius is 700,000 km). Movies of the corona from LASCO show the large-scale structures in the corona as they rotate with the rest of the Sun (the solar rotation period as viewed from the Earth is 27 days or so, with slight latitude

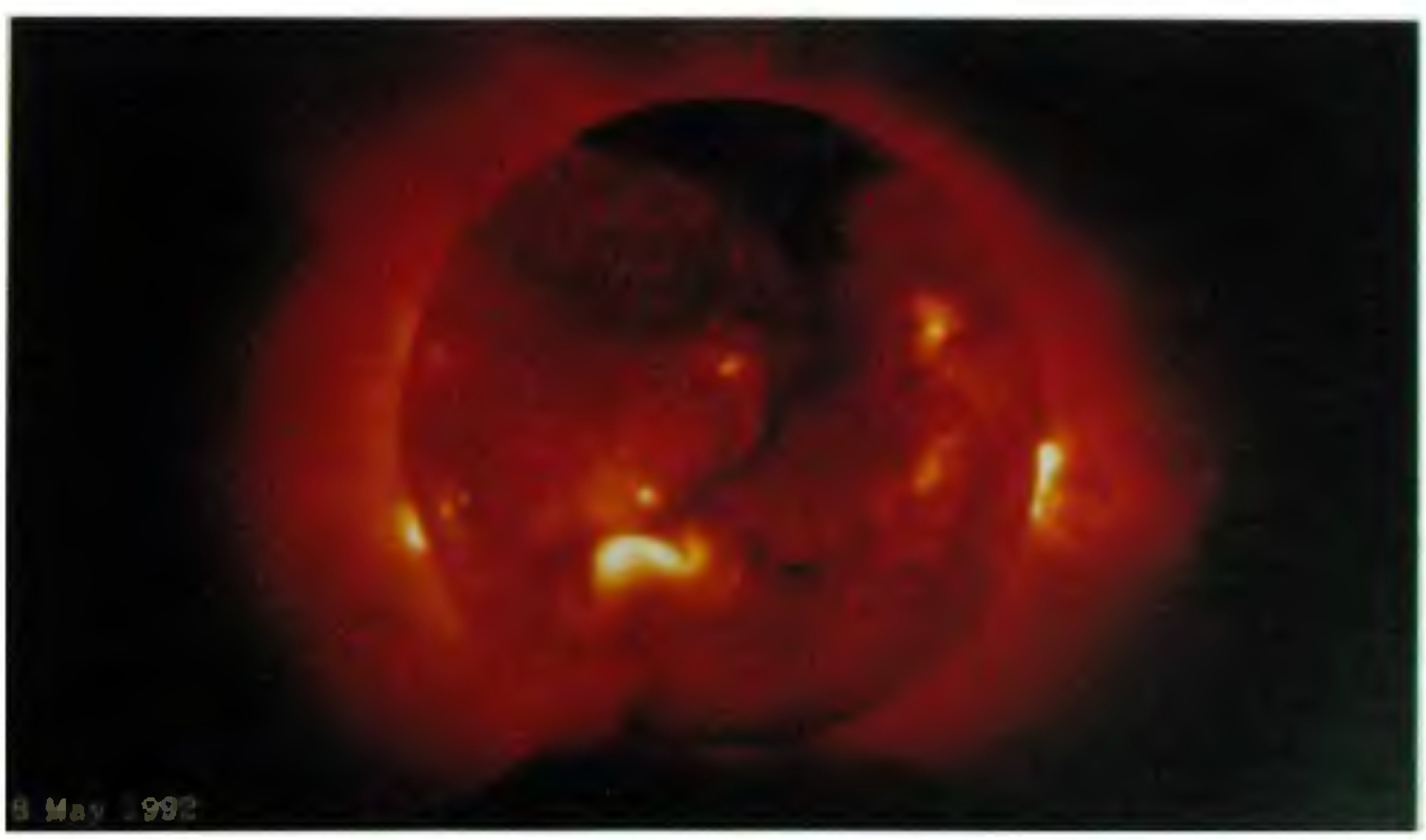

Figure 2. *Yohkoh* soft X-ray telescope (SXT) image of the Sun's corona on 8 May 1992 (Courtesy The *Yohkoh* SXT Team).

dependence), but more particularly they show the large ejections of coronal mass in the form of huge bubbles, moving out with velocities of several hundred kilometer per second (typically) that, on colliding with the Earth and other planets in the solar system, give the well-known magnetic storms and associated phenomena that have become a matter of widespread concern for telecommunications in recent years.

The Transition Region and Coronal Explorer (TRACE) is a highly successful spacecraft observatory, operated by the Stanford-Lockheed Institute for Space Research, which was launched in 1998 and has imaging capabilities that are truly staggering. The spatial resolution is of order 1 arc second (725 km), and there are wavelength bands covering the Fe IX, Fe XII, and Fe XV lines which EIT observes as well as the Lyman-alpha line at 121.6 nm. Movies made by stringing together many images of, for example, active regions reveal a vast wealth of detail, with the coronal loops showing continuous brightenings and motions. A remarkable feature is that the loops often have widths which are no more than the spatial resolution of TRACE, and so they are probably thinner than 1 arc second.

Some of the *SOHO* instruments are able to obtain spectra in the ultraviolet region, and such spectra are of great use in 'diagnosing' (i.e. deducing the prevailing physical conditions in) the emitting plasma. The corona is an almost fully ionized plasma, i.e. is composed of mostly protons and electrons, with the density of heavier ions only 10^{-6} of the proton density (hydrogen is by far the most abundant element in the Sun). However, the atoms of heavier elements like Fe or Si generally retain a few of their electrons, and hence the spectrum of the corona in, e.g. the extreme-ultraviolet range is characterized by numerous emission lines. The corona is generally optically thin in these lines, and their intensities often give important information about temperatures, densities, and flow speeds. Much work has gone into deducing particle densities from the ratios of particular lines which are density-sensitive, and as a result, we are now able to overlay density maps onto images of portions of the corona. We will discuss this further in Section 5.

3. Heating of the corona: Theory

There is evidence that the corona is heated by its magnetic fields, although the evidence is not direct. One vital piece of information that we are still unable to measure is the magnetic field in the corona. We are able to measure, with considerable accuracy, the photospheric magnetic field, using magnetographs that work on the Zeeman principle. This can be done for small regions so that a complete magnetic field map of the Sun's visible hemisphere (magnetogram) can be constructed. These are routinely available in, for example, the *Solar-Geophysical Data Bulletin* issued by NOAA. For vector magnetographs, all three components of the magnetic field can be deduced. But the measurements refer to magnetic field at the photospheric level, not in the corona. Although eventually infrared measurements may change this situation, the only

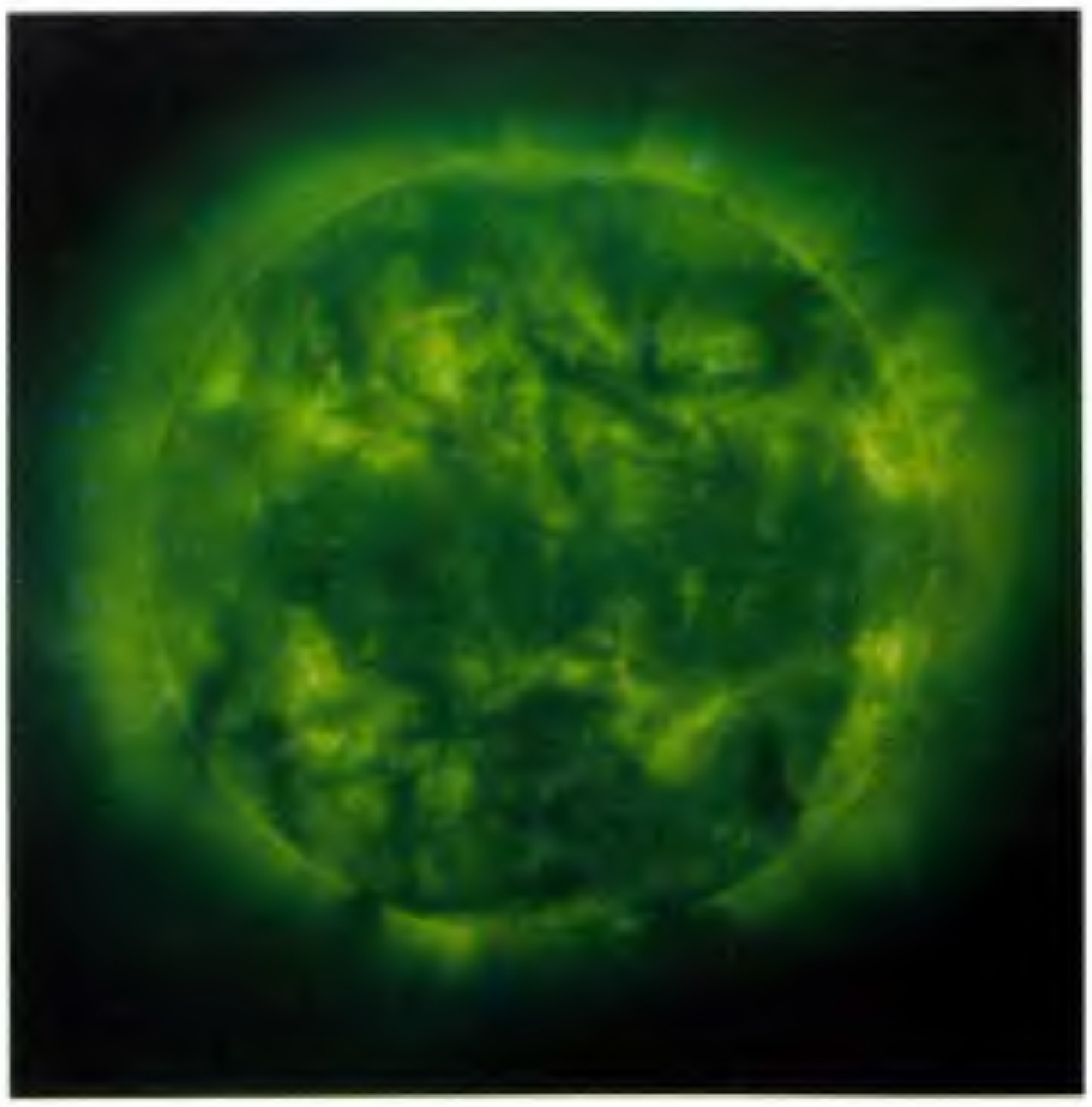

Figure 3. Image taken in the Fe XII 19.5 nm extreme-ultraviolet (EUV) line by the *SOHO* extreme-ultraviolet imaging telescope (EIT) instrument on 7 June 1999 (Courtesy The *SOHO* EIT Team).

way at present in which the coronal field can be deduced is through extrapolations of the photospheric field through the assumption, e.g. of a potential (current-free) or force-free field. We do find, however, that the photospheric field in active regions is more complex than in quiet regions, and it is also known that the active region corona is appreciably hotter (typically 4×10^6 K, depending on the nature of the active region) than in quiet regions (2×10^6 K, less in coronal holes at the poles). So there does seem to be a relation between field strength and heating.

A considerable theoretical problem with magnetic field heating is the fact that it requires the diffusion, and therefore reconnection, of magnetic field which implies a resistive plasma. However, the coronal plasma is on the contrary highly conducting. Using Spitzer's expression for plasma resistivity, $\eta = 10^3\ T^{-1.5}$ Ohm m (T is the temperature in K), we find for $T = 2 \times 10^6$ K, $\eta = 4 \times 10^{-7}$ Ohm m, only a factor 20 or so higher than solid copper, a familiar example of an almost perfect conductor, at room temperature! Using the induction equation of magnetohydrodynamics, we find that the diffusion time for a magnetic field is extremely long unless the characteristic distance over which diffusion occurs is as short as a few meters when the diffusion time is a few seconds. Put another way, the magnetic Reynolds number R_m, measuring how tied the magnetic field is to the plasma, is typically 10^6 to 10^{12} for the corona, indicating that the field is completely 'frozen in' to the plasma. However, reconnection requires R_m to be very small, much less than one in fact. Thus, only if the length scales are very small can one achieve magnetic reconnection. Very small length scales do occur in the region of neutral points or current sheets, where there are steep magnetic field gradients which give rise to large currents. It is thought, then, that such geometries are important for coronal heating if this is by very small energy releases, known (from the original work on the subject, by Parker[2]) as nanoflares. Some 10^{16} J are released in a nanoflare, i.e. 10^{-9} of a large solar flare, and many energy releases like this occurring all over the Sun, quiet regions as well as active regions, could account for heating of the corona. However, it is doubtful whether this mechanism would apply to coronal hole regions where the field lines are open to interplanetary space.

The above reasoning applies equally to the competing wave heating hypothesis of coronal heating, in which magnetohydrodynamic waves generated by photospheric motions (e.g. granular or supergranular convection motions) are dampened in the corona. In this case, we need conditions such that the magnetic field changes occur in a shorter time than, say, the Alfvén wave transit time across a closed structure like an active region or quiet Sun loop. The literature for wave heating of the corona is very considerable, but we may briefly summarize it by stating that the waves, generated by turbulent motions in the solar convection zone or at the photosphere, may be surface waves in a loop geometry, or body waves which are guided along the loops and are trapped. The work of Porter, Klimchuk and Sturrock[3] shows that short-period fast-mode and slow-mode waves (periods less than 10 s) could be responsible for heating since only for them are the damping rates high enough.

It is worth mentioning that MHD waves need not be generated by photospheric motions. Axford and McKenzie[4] have proposed a 'furnace' model in which small loops convected into the chromospheric network undergo reconnection and launch high frequency waves which can heat the corona (to a few million degrees) through ion-cyclotron resonance dissipation and rapidly accelerate the wind up to high speeds (~ 750 km/sec) within a few solar radii.

4. Observational evidence: Transient brightenings

Early observations with the high resolution telescope and spectrograph (HRTS) by Brueckner and colleagues[5] showed that the profiles of the strong C IV (transition region) ultraviolet (154.8, 155.1 nm) line pair, emitted at 100,000 K, showed much dynamic activity that could be broadly classified into turbulent events (speeds up to 250 km/s in small areas) and jets (speeds up to 400 km/s). The energy contained in the jets amounts to a 'microflare' (i.e. up to 10^{19} J), and it was considered that shock waves generated by a jet could heat up the corona. Enough energy and mass are contained in the jets, assumed to occur over the whole Sun, to satisfy the requirements of the corona and its dynamic extension, the solar wind.

Such phenomena are just an example of the many transient events that occur in the solar atmosphere. Shimizu and colleagues[6] have been studying the *Yohkoh* SXT data for active regions, and they find numerous small brightenings in active region loop structures having energies of the order 10^{20} J, i.e. comparable to microflares. Similar X-ray flares have been noted at higher energies by Lin and colleagues in 1984. Again there is a possibility that the energy supplied by these small active region events is sufficient to heat the corona outside coronal holes, though present indications are that it is short by a factor of about 5. Even smaller events – 'network flares' – have been noted outside of active regions by Benz and Krucker and later by Pres and Phillips[7] (Figure 4) in studies of *Yohkoh* SXT and *SOHO* EIT data. Here, the energies of the events are much less (down to only 100 times a nanoflare) but then the energy requirements of the quiet (i.e. non-active region) solar corona is correspondingly less. Within coronal holes, where the soft X-ray background is very small indeed, Koutchmy has seen tiny coronal 'flashes' which have energies of order 10 times a nanoflare.

In the extreme-ultraviolet (EUV), very small brightenings have been noted by various authors using *SOHO* data in quiet-Sun regions. It would appear that these were visible in earlier spacecraft data such as those from the

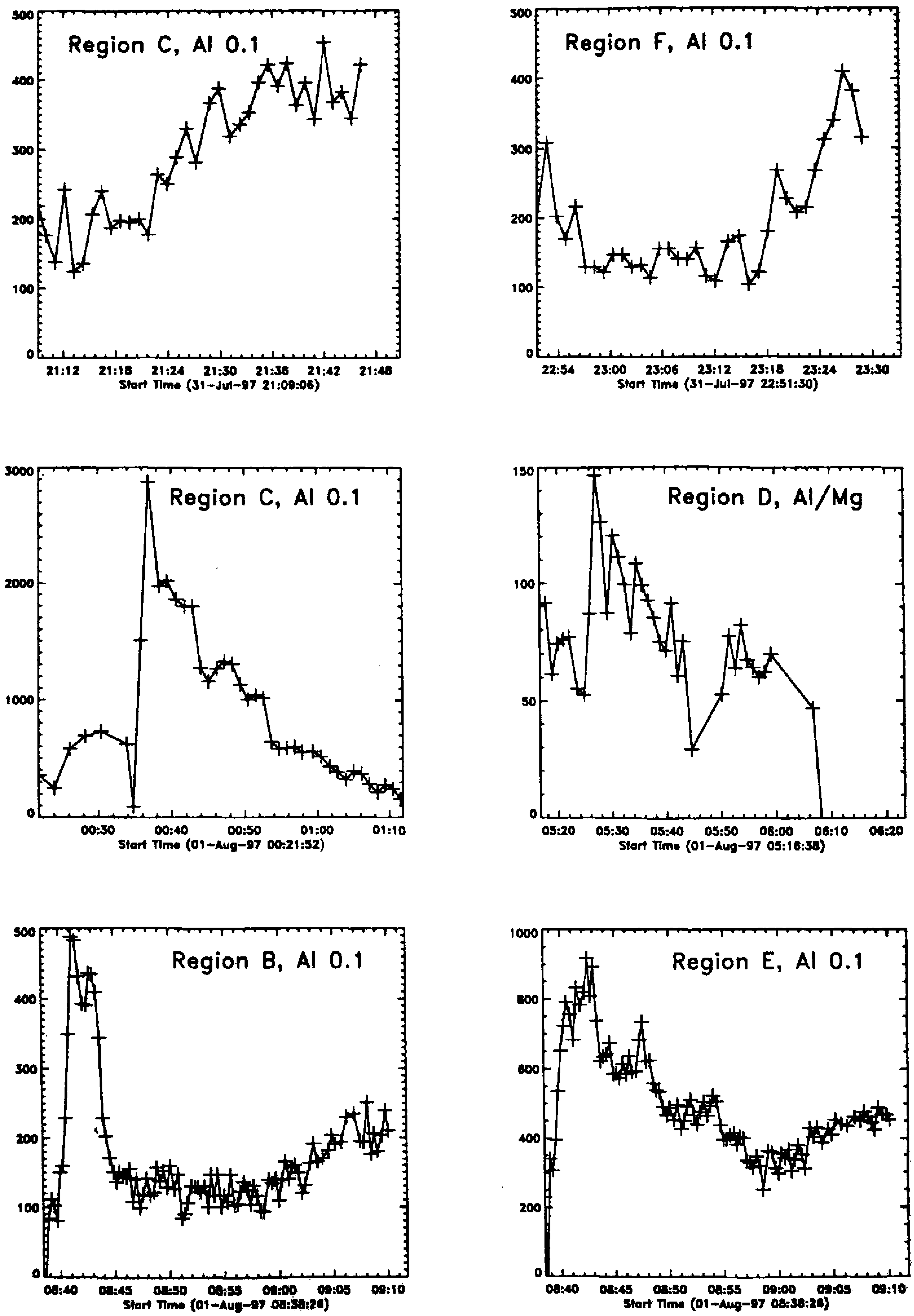

Figure 4. Examples of soft X-ray quiet Sun 'network flares', noted outside of active regions (Courtesy P. Pres).

OSO series from the 1970s. A comparison by Pres of network flares and these so-called 'blinkers' reveals a strange lack of correlation, with the EUV transients in quiet regions being apparently much more numerous than their X-ray counterparts.

Table 1 gives some indication of the thermal energy rate (W) deduced from observations of various transients in either X-rays or the EUV. As the total radiative power of the entire quiet-Sun corona is several 10^{19} W, it appears that the numerous EUV quiet-Sun transients might offer the best possibility of heating, assuming that the Parker nanoflare hypothesis is correct.

5. Physical characteristics of the corona

It is clear from eclipse or spacecraft images of the corona (Figures 1 and 2) that the corona is highly structured, and that the hot plasma making up the corona is confined to intricate magnetic field patterns. Particle densities and temperatures can be derived for different coronal regions using a variety of methods. For example, measurements of the surface brightness of the white-light corona yield electron densities, since the emission is by Thomson scattering of photospheric light off free electrons. Near the base of the corona the measured electron densities are a few times 10^{14} m^{-3}, though this is strongly dependent on whether the feature is a quiet region (smaller densities) or within a complex of active region loops (larger densities). The densities are further reduced within coronal holes. The density falls off rapidly with height: at 5 solar radii from Sun centre, the density is 10^{11} m^{-3}, while at the distance of the Earth's orbit (where the corona is in the form of a freely flowing wind) the density is less than 10^7 m^{-3}. As indicated earlier, temperatures vary in the corona from place to place, with maximum values in highly complex active regions (up to 4×10^6 K) and minimum values in the polar coronal holes (slightly less than 10^6 K). In general, then, densities and temperatures are correlated.

To illustrate the fact that the coronal gas is strongly dominated by the magnetic field, we find that the magnetic pressure $B^2/2\mu$ is generally many times more than the gas pressure NkT (N = particle number density, k = Boltzmann's constant). For a typical active region, magnetic pressure might be as much as 50 Pa, but the gas pressure is perhaps a factor of almost 10 less.

Table 1. Energetics for EUV and X-ray transient events in the quiet Sun corona

No. of events h^{-1}	Thermal energy rate (W)	Event type
40,000 brightenings	3×10^{19}	EUV transients
1,200	2×10^{18}	Small network flares
100	2×10^{18}	Large network flares

The data in the table are based on recent publications using *SOHO* and *Yohkoh* observations (see References).

Measurements of densities and temperatures using X-ray or ultraviolet data are possible, particularly using line intensities. Most regions in these lines are optically thin, though there are notable exceptions like in the hydrogen Lyman-alpha line and the other strong resonance lines. The line intensity is a function of temperature, through the ionization fraction of the emitting ion (a strongly peaked curve) and the excitation rate from the ground energy level of the ion to the upper level giving rise to the line emission. Excitation of most ions emitting lines in the X-ray and ultraviolet ranges is due to collisions of free electrons with the ions. Very roughly we can assign a single temperature to an ion, e.g. three-times-ionized carbon, which gives rise to the C IV 154.8/155.1 nm line doublet, corresponds to a temperature of about 100,000 K, approximately the maximum fractional abundance of the C^{+3} ion in 'ionization equilibrium', i.e. a balance between collisional ionization processes and radiative and dielectronic recombination processes which occurs in the solar corona. These fractional abundances can be calculated using atomic data, and there are many publications which give values as a function of temperature (in general there is practically no density dependence).

Excitation of the lines can be calculated to much higher accuracy than was possible about 20 years ago as there are sophisticated atomic codes which take into account resonances in the collisional cross sections. Among these is the close-coupling R-matrix code developed at Queen's University Belfast. As a result, there are a number of line pairs recognized in especially the extreme-ultraviolet part of the spectrum which are sensitive to electron densities. This fact is very useful as nearly all other methods of getting densities are indirect. Thus, a measured line intensity of a feature leads to a value for the 'emission measure' $N_e^2 V$ (V = volume, N_e = electron number density). This combined with a measured value for V (e.g. from image data) gives N_e. However, this technique is often quite imprecise since the presence of fine structure within the feature, if unresolved by the instrument taking the observations, renders the value of N_e to be merely a lower limit. Account then has to be taken of a 'filling factor', often much less than one. Spectral line diagnostics for solar plasmas have been discussed in an accompanying article of this issue by Dwivedi, Mohan and Wilhelm[8].

The Coronal Diagnostic Spectrometer (CDS) on *SOHO* has been widely used to get densities, and it is now possible to construct maps of regions of the Sun showing electron densities. Gallagher and colleagues[9] at Queen's University Belfast and Rutherford Appleton Laboratory have been active in this. Two examples of suitable density-sensitive lines in the wavelength range of CDS are those due to Si IX and Si X, both emitted at around

1.3×10^6 K. This value of temperature makes them ideal for studying the quiet corona. Figure 5 shows the positions of scans using a pair of lines emitted by each ion around the Sun's limb with the CDS instrument in February 1996, and Figure 6 shows the resulting scan with light areas indicating measured electron densities from each ion, the vertical scale being position angle around the Sun's limb. It shows clearly the presence of higher densities in low-latitude regions (N_e around 4×10^{14} m^{-3}), while near the south pole (position angle 180 degrees) the electron density is at least a factor 4 lower. The density profile with position angle at three radial distances out to 1.2 solar radii agrees remarkably well with a recent analytical model that has been developed for Sun-like stars[10].

6. Observational evidence: Wave motions

Despite the fact that the nanoflare hypothesis seems to be observationally plausible (as indicated in Section 4), MHD waves may well be implicated in the heating of the corona, and it is important to look for signatures of them. It is, for example, unlikely that nanoflares could heat the corona in the regions of open field lines such as occur in polar coronal holes, yet it appears that the corona is still hot in these open-field regions. A basic difficulty seems to be that theoretical predictions indicate that MHD waves having only a short period (less than 10 sec) are likely to be effective in the heating, since only for such waves are the damping rates sufficiently great. However, spacecraft imaging, limited as it is by the rate at which data are telemetered to the Earth, is necessarily rather slow. It takes about 2 min for any instrument on *SOHO* to produce an image of even relatively small portions of the Sun.

There is hence still considerable interest in observing the visible-light corona during total eclipses from the ground, since one can use high-speed electronic cameras to obtain rapid imaging of particular coronal structures. A pioneer in this work has been Pasachoff[11], who has tried this kind of experiment at various eclipses around the world since the 1980s. Analysis of his best results indicate the presence of a slight peak in Fourier spectra at frequencies of 0.5–1 Hz. This has been seen in more recent eclipses, including the 1998 eclipse in the Caribbean. Other measurements using ground-based white-light coronagraphs have been taken, notably by Koutchmy[12] at the US National Solar Observatory/Sacramento Peak some years ago. Here searches were made for periodic modulations in both the intensity and velocity of the green line, with evidence of periods equal to 43, 80 and 300 s (the last is probably related to the familiar five-minute oscillation seen with photospheric Fraunhofer lines).

While Pasachoff continues to develop his instrument with colleagues at Williams College, Massachusetts, a group including Rutherford Appleton Laboratory, Queen's University Belfast, and the Astronomical Institute, University of Wroclaw in Poland have been developing a fast-imaging system with charge-couple device (CCD) cameras that can image up to 50 frames a second with a specially adapted computer that 'grabs' images, placing the data on to large-capacity hard discs for later analysis. The cameras were developed by EEV, a company specializing in CCD cameras in Chelmsford, UK, and the computer hardware and software were developed by Carr-Crouch Computer Company, Maidenhead, UK. The system, called the solar eclipse coronal imaging system (SECIS),

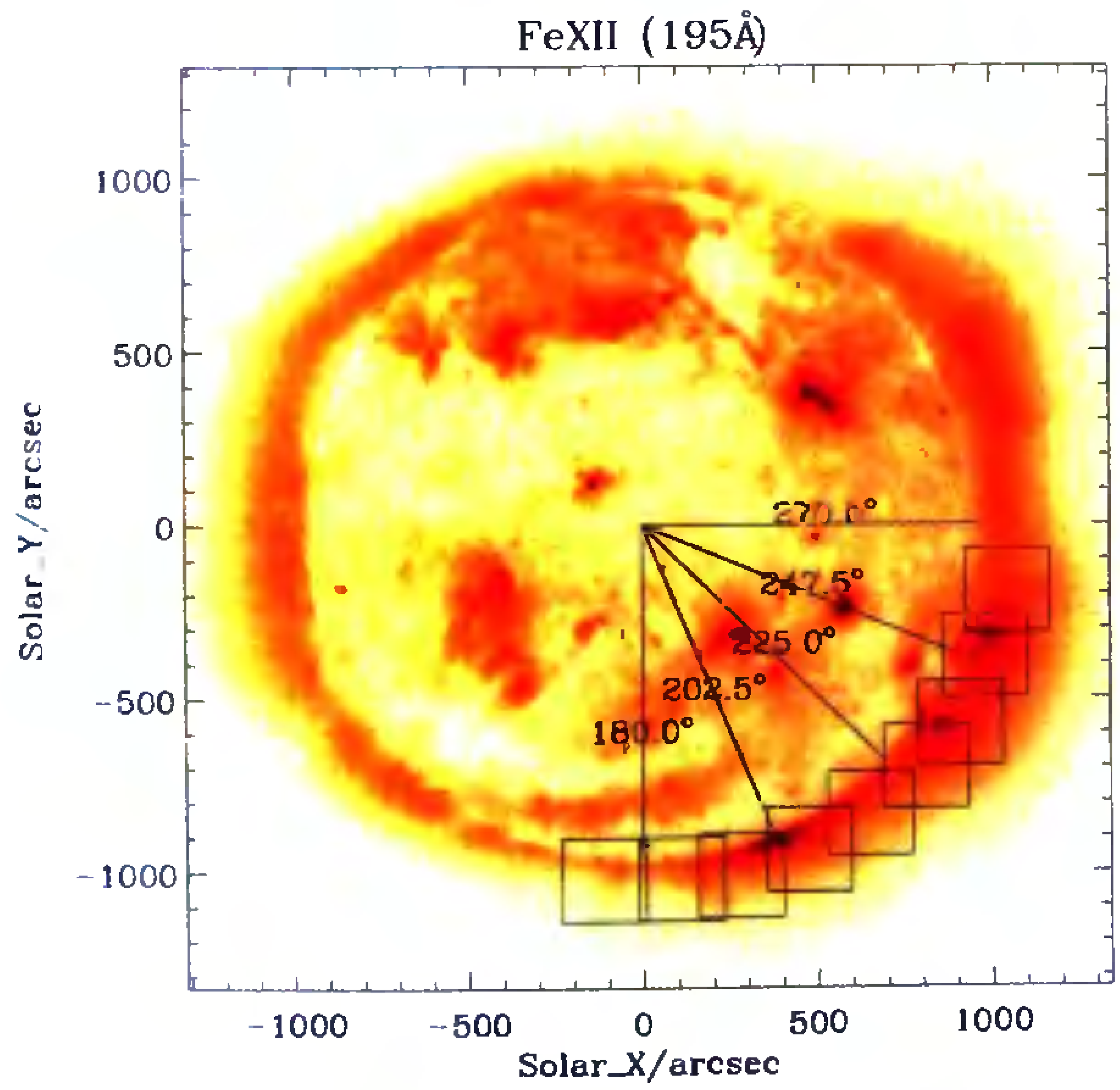

Figure 5. *SOHO* EIT image of the Sun showing positions of scans with the CDS instrument.

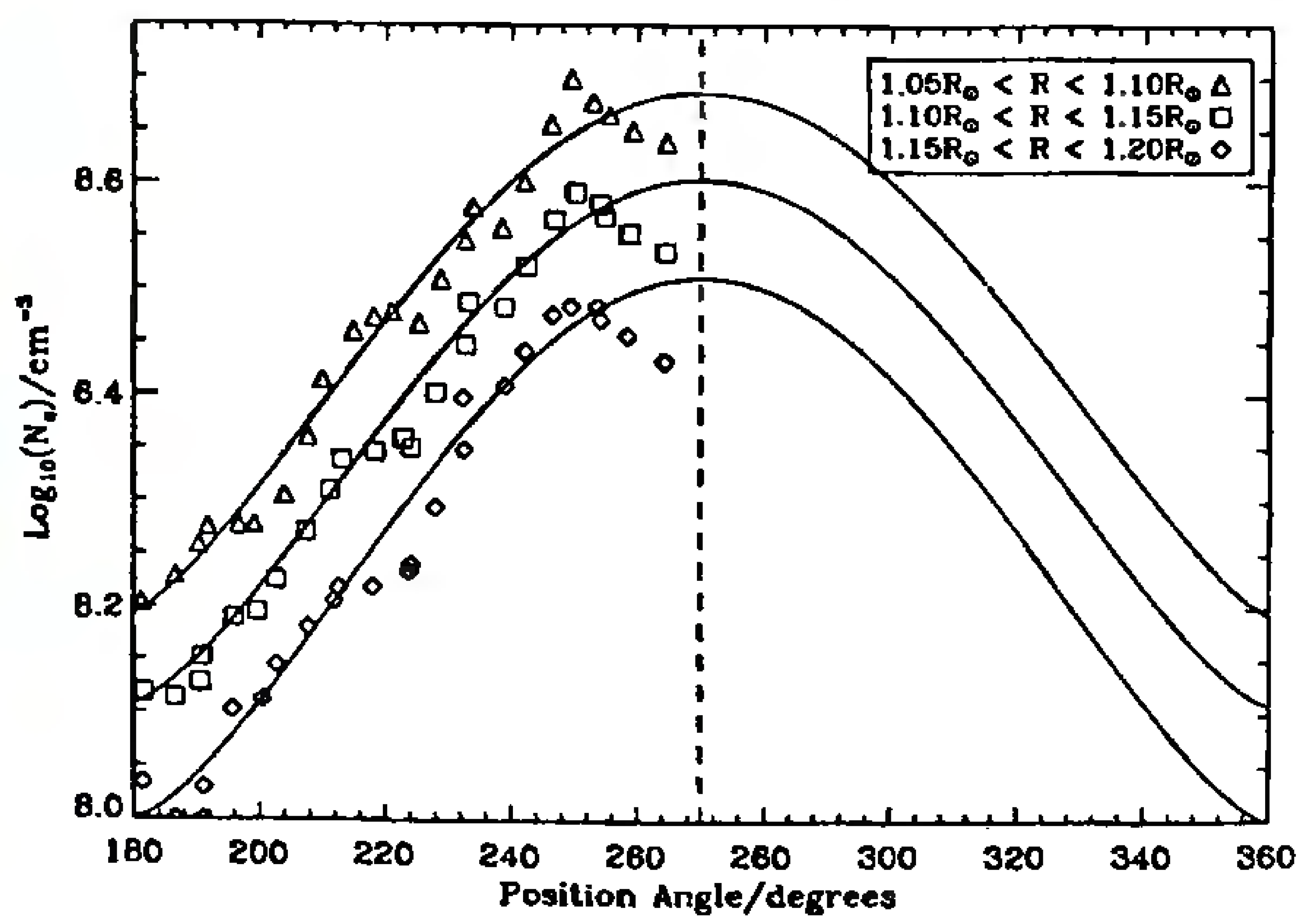

Figure 6. Electron density plot showing variation of electron density with position angle round the Sun (see Figure 5). Density scale is on the right. The left panel is using a Si IX line ratio, that on the right a Si X ratio (Courtesy P. T. Gallagher).

has been tested on a number of occasions already, the first being during the 1998 eclipse and most recently on 11 August 1999, the last total solar eclipse of this millennium. Scientifically useful results were obtained during a run on the Evans Coronagraph Facility at Sacramento Peak. Preliminary results, with one channel (using a green-line filter), are shown in Figure 7, showing a system of active region loops on the limb with initial Fourier analysis done by Gallagher. Taken at face value, there is very slight evidence for excess power at small (less than 5 Hz) at a location (A) within the active region loops but none in the more distant location (B) where the coronal

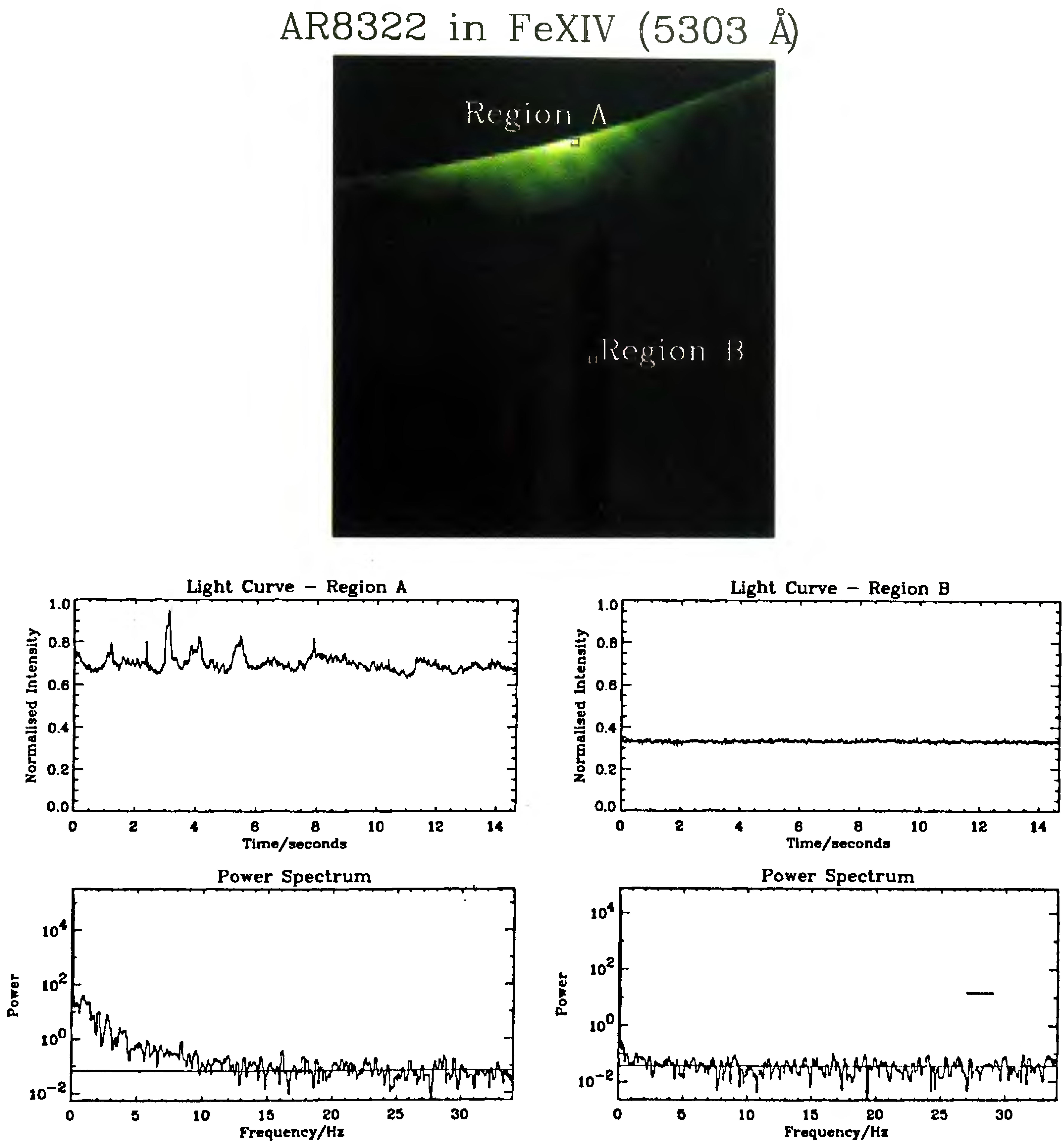

Figure 7. Image of coronal loops on the solar limb in September 1998 with preliminary Fourier analysis of two points in the image (A is within the coronal active region, B is considered to be non-coronal or sky brightness) (Courtesy P. T. Gallagher).

signal is negligible compared with sky (terrestrial) background.

7. Concluding remarks

A large amount of information concerning the physics of the solar atmosphere has become available in recent years and it is taking some time to digest the new data. The exact reason for heating the solar corona is still not known for certain, but there is much evidence from spacecraft observations that, in regions where there are complex magnetic field geometries or at least the presence of closed loops, heating by numerous small flare-like releases of energy is adequate to explain the energy requirements of the corona. In coronal holes, i.e. regions of open field lines, this is less likely to be true and many consider that heating proceeds through the damping of MHD waves, which may still have a role in the heating of the corona in closed-field regions. At present this can only be investigated using ground-based instruments since the periods of MHD waves which have sufficiently large damping rates are likely to be very small, of order a few seconds. Spacecraft imaging is too slow to search for such periodicities.

1. Phillips, K. J. H., *Guide to the Sun*, Cambridge University Press, Chapter 5, 1995.
2. Parker, E. N., *Astrophys. J.*, 1988, **330**, 474–479.
3. Porter, L. J., Klimchuk, J. A. and Sturrock, P. A., *Astrophys. J.*, 1994, **435**, 482–501.
4. Axford, W. I. and McKenzie, J. F., in *Cosmic Winds and the Heliosphere* (eds Jokipii, J. R., Sonett, C. P. and Giampapa, M. S.), University of Arizona Press, Tucson, 1997, pp. 31–66.
5. Brueckner, G. E. and Bartoe, J.-D. F., *Astrophys. J.*, 1983, **272**, 329–348.
6. Shimizu, T., *Pub. Astron. Soc. Japan*, 1995, **47**, 251–263.
7. Pres, P. and Phillips, K. J. H., *Astrophys. J.*, 1999, **510**, L73–L76.
8. Dwivedi, B. N., Mohan, A. and Wilhelm, K., *Curr. Sci.*, 1999 (this issue).
9. Gallagher, P. T., Mathioudakis, M., Keenan, F. P., Phillips, K. J. H. and Tsinganos, K., *Astrophys. J.* (submitted).
10. Lima, J. J. G., Priest, E. R. and Tsinganos, K., *The Corona and Solar Wind near Minimum Activity*, ESA SP-404, 1997, pp. 521–526.
11. Pasachoff, J. and Ladd, E. F., *Solar Phys.*, 1987, **109**, 365–372.
12. Koutchmy, S., Zugzda, Y. D. and Locans, V., *Astron. Astrophys.*, 1983, **120**, 185–191.

ACKNOWLEDGEMENTS. We thank colleagues for allowing us to use their work to illustrate this article, in particular P. T. Gallagher, F. P. Keenan, P. Pres, and members of the *SOHO* (EIT) and *Yohkoh* experiment teams. We are indebted to K. Wilhelm for critical reading of the manuscript.