November could be felt beyond the year 2000. A more hopeful recent development has been the spread of 'glasnost' to the Soviet space programme. The enormous scale of the Soviet space programme is indicated by noting its average launch rate of 2 satellites per week. Further, in the MIR system, the USSR have had a manned space station operating in orbit for over a year, while the US, Japan and Europe are still only talking of their plans for a space station for the mid-90s. The recent offer to Western countries to launch their instruments on Soviet spacecraft opens an important new prospect for space astronomers in the years ahead. Given the present uncertainties in both the NASA and ESA programmes, the period to the end of the century could see a major and beneficial shift in the influence of the Soviet Union in space science (and astronomy).

K. Pounds
X-ray Astronomy Group
Department of Physics
University of Leicester
University Road
Leicester LE1 7RH
England.

GIANT STARSPOTS AND STELLAR FLARES: THE VIEW FROM SPACE

Patrick B. Byrne, Armagh Observatory.

1. Spots and Flares on the Sun

The surface or photosphere of the Sun, our nearest star, is at a temperature close to 6000 K. At this temperature the materials of which it is made are gaseous and substantially ionized, i.e. one or more electrons have been stripped from each atom. Thus, the photosphere of the Sun comprises a plasma. Since a plasma is made up of electrically charged ions and free electrons it can be both a source of magnetic fields and is likewise affected by them.

The Sun's energy comes from thermonuclear reactions taking place deep within its core. This energy is carried outward near the surface by convection. The convection of the electrically charged plasma gives rise to a dynamo effect, generating powerful magnetic fields. These magnetic fields, in turn, act on the surrounding plasma and give rise to a range of phenomena known collectively as solar activity. Among the activity phenomena seen on the Sun are sunspots, flares and the corona.

Sunspots are large dark areas of the Sun's surface which are some 1500 – 2500 K cooler than the surrounding photosphere. By terrestrial standards they are immense, even modest examples being large enough to swallow the entire Earth. In spite of their large size by terrestrial standards, a typical spot will only occupy $\sim 10^{-4} - 10^{-5}$ of the solar surface. The largest spot group ever recorded occupied about one thousandth of the Sun's surface area.

The physical cause of sunspots lies in locally strong magnetic fields. Magnetic field strengths in the darkest parts of a large sunspot may be as large as 0.5 T (the Earth's magnetic field strength is, for comparison, $\sim 10^{-4}$ T). These magnetic fields interfere with the convection of the plasma comprising the photosphere and, starved of heat from below, the magnetic area cools, ultimately giving rise to a spot.

Each spot or spot group is in itself ephemeral, average-sized spots lasting a few days. Exceptionally large examples may persist for several weeks, however.

A sunspot is only one manifestation of the solar magnetic fields. It is generally part of a more complex magnetic structure called an
Active Region. Within this region the magnetic field structure may dominate the motions of the gases and give rise to flares, prominences and local heating of the multi-million degree corona.

*Active Regions* are complex areas of strong magnetic field on and above the solar surface. Usually a strongly active region has a sunspot group associated with it where the magnetic field cools the photosphere.

The magnetic field is not confined to the solar photosphere, however. It may arch high above into the surrounding chromosphere and corona. Here the magnetic field both confines and heats the gas. The coronal gas attains temperatures of a few million degrees, while in the immediate vicinity of the larger magnetic loops it may be up to $10-20$ million degrees.

The result is that the corona has a very non-uniform appearance, being brightest in the denser, hot loops. This structure is particularly striking in X-rays emitted by the hot gas.

Magnetic heating of the cooler, denser gas gives rise to less extreme temperatures, in temperature regimes called the chromosphere ($\sim 6,000 - 20,000 \, \text{K}$) and transition region ($\sim 20,000 - 1,000,000 \, \text{K}$). Each has its own characteristic radiation. That from the chromosphere is generally in optical and near-ultraviolet light, while that from the transition region is usually in the near- to far-ultraviolet.

*Flares* are impulsive releases of energy occurring usually in magnetic active regions. They involve the release of very large total energies, typically $\sim 10^{33} \, \text{J}$, most of which is released within about a minute. The effects of solar flares are felt here on Earth, a hundred and fifty million kilometers away, as radio interference and the Aurora Borealis.

A flare occurs when a magnetic loop within an active region is twisted and stressed. The stressed loop reconnects and the stored energy is suddenly released. This process is analogous to the snapping of a twisted elastic band. As the field reconnects, local electrons are accelerated to velocities close to the speed of light.

The resulting beam of high-speed electrons is constrained to travel along the magnetic field lines. While they are in the coronal part of the magnetic loop the density is low and they travel unimpeded. When they hit the denser chromosphere, however, they are collisionally braked and transfer their kinetic energy to the local plasma, heating it to $10-20 \, \text{million}$ degrees. Intense hard X-radiation is generated at this point and the flare has begun.

The hot gas expands rapidly, still confined by the magnetic field, and fills the loop. Here it cools by radiating its energy away, mainly as soft X-rays, and dying away over the subsequent hour or so (see Byrne 1986).

There is no good reason to suspect that the Sun is unique among the stars in displaying these signs of magnetic activity. If the Sun were placed at the distance of even the nearest star, however, the presence of these various phenomena could not be detected directly. Thus, if we are to detect magnetically related phenomena on other stars, they will have to be on a scale larger than the solar one by orders of magnitude.

2. Starspot

Unlike the Sun, stars' surfaces are not resolved. Therefore, the existence of surface activity must be inferred by more indirect means. The principle of the method used is illustrated in Figure 1. Here a rotating star with a single large dark spot results in a variation with time of the light detected at Earth. As the star spins on its axis the spot is alternately in or out of view. When it is in view the star appears darker while, half a rotation later, the star is seen to recover its former brightness. Observations of real light curves show that the spot distributions are quite complex (Byrne and Marang 1987).

![Figure 1. The upper part shows the rotation of a spotted star while the lower demonstrates the resulting variation of the star's light with time.](image)

The spot distribution inferred from these types of observations varies from season to season, influenced by the combined effects of...
relative motion of the major spot groups caused by differential rotation, and the growth and decay of individual spots (Panagi and Doyle 1987). The lifetime of a typical spot distribution is similar to that of the largest solar spots. Their sizes, however, are enormously greater. The largest starspot group inferred directly from an optical light curve occupied at least 16% of the surface area of the star (Byrne and Marang 1987).

Observations with the International Ultraviolet Explorer (IUE) satellite have allowed us to investigate the magnetically-heated outer atmospheres of these spotted stars. Here we record emission lines formed in the temperature regime from about 8000 – 200,000 K, i.e. in the stellar chromosphere and transition region. A typical spectrum is shown in Figure 2 with the principal spectral lines and their temperatures of formation indicated. The solar experience would lead us to expect enhanced heating above an active region associated with a sunspot. This has indeed been observed with IUE on the spotted star II Peg (Rodono et al. 1987) (Figure 2). Furthermore, analysis of the spectra has also shown that the gas density is also enhanced in these regions (Byrne et al. 1987).

The location of these active regions on the stellar surface can also be determined by means of a technique known as "Doppler Imaging". All of the spotted stars are rapidly rotating. If a star were uniformly covered with material emitting a particular spectral line, then a smooth emission-line profile would result (solid line profile, lower panel Figure 3). On the other hand, if a region of the star (hatched in Figure 3) emits more than average, an excess emission feature results at a wavelength corresponding

![Figure 2. An IUE spectrum of the spotted star II Peg. The upper panel gives the mean spectrum when the spot is out of view and the lower that when the spot is visible. Some bright emission lines are identified and their temperatures of formation given.](image-url)
to its Doppler shift and which moves with time as the star rotates. Detailed consideration of such line-profile observations allows us to locate active regions on the stellar surface. This technique has been successfully applied to the RS CVn star AR Lac (Walter et al. 1987).

Figure 3. The principle of Doppler Imaging is schematically illustrated. If a rapidly rotating star is uniformly covered with material emitting a spectral line, then a smooth line profile results, each sector of the star contributing to the final line profile (solid line) in proportion to its projected area and at a wavelength determined by the velocity of that sector along the observer's line-of-sight. If, however, there exists an active region in one sector (hatched area), then the contribution of that sector to the line profile will be increased and a “bump” seen (dashed line). This feature will move across the profile as the star rotates.

3. Stellar Flares

Stellar flares are recorded as impulsive brightenings of the star, taking place in times as short as a few seconds (Byrne 1983). The subsequent decay may take from 15 minutes to several hours. A typical optical light curve is given in the upper panel of Figure 4. The most remarkable aspect of stellar flares is their total energies. In optical light alone they yield up to $10^6$ times the energy emitted by a typical solar flare at all wavelengths.

Simultaneous satellite observations of stellar flares show dramatic enhancements of chromospheric and transition-region lines (Butler et al. 1981). Unfortunately, the time and spectral resolution of these observations is not yet good enough for detailed studies to take place. Recent observations with the EXOSAT X-ray satellite, however, show that, in the time relationship between X-rays, optical light and chromospheric emission, stellar flares are similar to solar flares. Figure 4 shows this relationship. Note the much slower decay of the soft X-ray light curve as compared with the optical light (Doyle et al. 1987). The optical continuum light is thought to be produced when the accelerated electrons strike the stellar chromosphere and photosphere, while the soft X-rays are the result of radiative cooling of the filled magnetic loop.
ENERGETIC PARTICLES IN SPACE:
THE Giotto MISSION TO HALLEY’S COMET

D. O’Sullivan1, P. Daly1, E. Kirsch2, S. McKenna-Lawlor3, A. Thompson4 and K.-P. Wenzel4

1. Dublin Institute for Advanced Studies, Ireland.
2. Max Planck Institute for Aeronomic, Lindau, FRG.
The paper was presented by D. O’Sullivan.

1. Introduction

The very successful encounter of the Giotto and other spacecraft with Halley’s Comet just over eighteen months ago produced a wealth of data unprecedented in the history of cometary studies. The encounter provided the first ever in situ measurements of the comet’s environment and included the EPA experiment designed to study energetic particles around Halley. Here, energetic is defined relative to energies usually associated with plasmas rather than cosmic rays, and the particle studies which form the basis of this talk encompass the energy range from tens of keV up to and including the MeV region. The EPA instrument was the only one aboard the Giotto spacecraft capable of investigating this energy region.

2. The EPA Instrument

The EPA instrument consisted of three semiconductor telescopes T₁, T₂, T₃ and associated electronics. T₁ was oriented at 45 deg. to the spin axis of the spacecraft and viewed the backward hemisphere with respect to the spacecraft trajectory while T₂ and T₃, at 135 deg. to the spin axis, viewed forward. This geometry, along with the spacecraft spin (period 4 sec) made three-dimensional observations possible throughout the mission. A detailed description of the instrument may be found in McKenna-Lawlor et al. (1987).