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STRUCTURE OF THE SOLAR CORONA

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Abstract

Solar eclipses established the existence of the outermost region of the solar atmosphere, the solar corona, extending to several solar radii and exhibiting open and closed magnetic field patterns The density and the temperature of the solar corona were inferred from the optical spectrum Through the use of coronagraphs on and above the earth and finally on the skylab and with enlarged range of spectral, spatial and temporal resolutions, a multitude of structures formed by the complex intrplay of density, temperature and magnetic field gradients, have been revealed The morphology and dynamics of these structures which set up a link between the interior of the sun and the solar wind, are briefly described in this review

1 Introduction

The first observations of coronal green line were taken in Iowa during the August 7, 1869 solar eclipse Charles Young found a green emission line in the outermost part of the solar atmosphere Other lines known as the red line and the yellow line were observed in subsequent eclipses These lines defied identification for several decades, as they did not match to any of the then known lines Around 1940, the emission lines of the corona were finally identified to be the emission lines of highly ionized metals under extreme conditions of high temperatures and low densities Thus the green line is from Fe XIV, the yellow from Ca XV and the red from Fe X These identifications led to the first indication of a million degree corona

2. Corona, Revealed by Solar Eclipses

Eclipse observations established the source, composition density, temperature and magnetic field of the corona All shapes in the corona are due to the electrons being confined or otherwise by the magnetic field White light is mainly the photospheric light scattered by these patterned electrons Eclipse pictures showed Radiating Rays prominantly seen at the solar poles These are electrons aligned along the magnetic field lines and became visible due to the scattered photospheric white light One notices streamers, usually restricted to solar equator, bulb shaped at the base, with narrowing neck continuing for millions of kilometers into the interplanetary space The streamers acquire their shapes because they form around closed magnetic arches that connect surface magnetic fields of opposite polarity At sunspot maximum, corona looks more complex and shows an abundance of streamers

Coronal magnetic fields have hold on electons only so far At larger distances, the electrons are free to escape and stream away into the solar wind Electrons protons and other particles are driven away by the heat of expansion of the million degree corona Bierman in 1951, pointed out that the observed outward acceleration and ionization of comet tails require a continuous flow of particles from the Sun The solar wind flow stretches out the ends of coronal streamers into the interplanetary space

Eclipses have their limitations Being of short duration, they cannot reveal the dynamical changes in the corona Eclipse pictures are two dimensional, one cannot tell whether the cross sections of streamers are flat, circular or elliptical One also misses the information on the direction of streamers with respect to earth, important for solar terrestrial relationship The interrelationship of coronal structures with other manifestations of solar activity like prominences and flares is also missing in the eclipse observations

3 Corona through the Coronagraph

Bernard Lyot in 1930, developed an alternative to solar eclipse, the coronagraph, which consists of a telescope in which the image of the photosphere was blocked by a small metallic occulting disk For quality observations, the stray light had to be eliminated Lyot discovered several lines in the visible and near infrared using long exposures With this instrument, only the innermost regions of the corona could be studied In order to extend the observations to the outer parts of the corona John Evans introduced an extra occulting disk which cuts the scattered light from the optics of the telescope This coronagraph was flown in an aircraft Soon, coronagraphs were operated from above the earth's atmosphere which made it possible to study the corona in other parts of the electromagnetic spectrum like in ultraviolet and X ray and to study the phenomena as far as six solar radii Many sophisticated instrument on Skylab revealed the corona, in such diversity and detail that completely new models were required to understand its workings It is no more a gentle uniformly expanding gas It is infested with structures large and small, magnetic and nonmagnetic, hot and cold dense and rare, curved and straight

Ultraviolet and X ray observations of the sun revealed coronal holes, coronal arches and loops, bright points as the basic building blocks of the solar corona Coronal holes are seen as spreading bald spots at th poles of the sun often stretching down to mid latitudes In X ray they look black indicating low densities and low temperatures The gas pressure in the holes may be a hundredth of what it is in X ray bright regions Coronal holes represent an open magnetic field configuration This geometry is suitable for the generation of high speed streams observed in the solar wind The study of those streams is very essential for understanding the solar terrestrial relationship as they cause magnetic storms affecting earth s magnetosphere Coronal holes rotate rigidly with the sun unlike the photosphere and chromosphere which rotate faster at the equator than at the poles

From the high quality Skylab pictures, one could follow the solar plumes which end in bright points The bright points are regions of concentrated magnetic fields and plumes seem to originate in the bright points Individual plumes rotate with the Sun and may persist for several days Plumes and spicules do not show any correlation in their evolution though they coexist in polar holes Bright points are found in active regions, in quiet regions in coronal holes, almost anywhere and everywhere Their average life span is about 8 hours though some of them are seen to flare up and fade in a few minutes while others may last for days The total magnetic flux associated with bright points is comparable to that in active regions This questions the monopoly of the sunspots as sole indicators of solar activity The bright points trace into the boundaries of the supergranular cells in the chromosphere Some of these are associated with small scale bipolar regions and are prone to flaring which can account for the heating of the solar corona Thus bright points emerge as another component in the description of solar activity, in addition to sunspot activity

In X ray wavelength corona can be observed all over the disc of the sun, unlike in eclipses X rays map the hottest regions like the intense cores of flares The corona looks a conglomeration of loops, arches, knots, all d lineating closed magnetic field controlled structures The hottest regions are manifestations of local regions of large energy release which may be due to anomalous joule heating, magnetic reconnection and or dissipation of

MHD waves The EUV line data has revealed temperature and density stratification within a single loop which has been modelled by Rosner, Tucker and Viana (1978) Priest (1982) Krishan (1983, 1985) and Krishan Berger and Priest (1987) The magnetic and velocity fields play an essential role in the stability structure and the energy balance of these loops (see Heating of Solar Corona , this proceedings)

Radio observations of the Sun gave the first indication of large transient disturbances travelling through the corona, now known as <u>coronal transients</u> or <u>coronal mass ejections</u> (CME) Skylab photographed gargantuan loops of coronal material rushing out at speeds varying from 100 1200 km/sec Sometimes as big as the disk of the Sun CME s are the biggest and most dynamic outbursts of the Sun into the interplanetary medium Since their number increases with the sunspot number, CME s offer one more description of th solar activity The mass content of CME's i very small inspite of their huge size The association with some disturbance in the olar wind indicates that CME's reach a far as the orbit of the earth, where they may result in atmospheric changes setting up a solar terrestrial relationship Such a large propelling force may be supplied either by a large flare or by the erruption of a prominence In either case, it is again ominpotent magnetic energy which when released in a sporadic manner throws the solar material into the outer corona and farther away Studies show that 70% of the CME's are propelled by prominence eruptions and the 30% triggered by flares originate lower in the solar atmosphere

At higher up in the corona the magnetic field weakens and electrons and protons are able to overcome gravity and escape into the solar wind The expansion of the solar plasma can be described a

$$nm\frac{d\vec{V}}{dt} = \quad \nabla p \quad nm\,\nabla\phi \tag{1}$$

where n is the density, m i mass of a proton V is velocity p the mechanical pressure and ϕ is the gravitational potential For radial and stationary expansion of a fully ionized gas, $\partial V/\partial t = 0$ Mass is conserved during expansion, therefore, one gets

$$nm\,\frac{dV}{dr} \qquad \frac{d}{dr}\;(2nK_BT)\quad \frac{nmGM_0}{r} \tag{2}$$

and

$$n\pi a^2 V = n_o V_o \pi a_o^2$$

Substituting in (2), one gets

$$\frac{1}{2}(V^2 \quad V_o^2) = \frac{2K_BT}{m}\ln\frac{V}{V_0} \qquad \frac{4K_BT}{m}\ln\frac{r}{r_o} + GM_o m(\frac{1}{r} \quad \frac{1}{r_o})$$

Here, the velocity of expansion is assumed to be a function of radial distance r, and the temperature T_0 for a given initial velocity V_0 In order to get typical solar wind velocity ~ 500 km/sec (required for acceleration of cometary ions), the temperature $T \sim 1\,5 \times 10^6$K for several solar radii Wind is significantly reduced with drop in temperature

In conclusion, Skylab observations have brought out the importance of several other features of solar activity in a way that a reassessment of the pre skylab models provides a new insight into the physical processes operating in making solar corona to be what it is Thus bright points are competing with coronal loops as heating units of the corona CME's and bright points emerge as important indicators of solar activity as sunspots Large scale magnetic structures show the ways to the interior of the sun and to the solar stellar connection A stellar corona can be defined as an extended atmospheric region at a temperature much higher than that of the photosphere; maintained by non

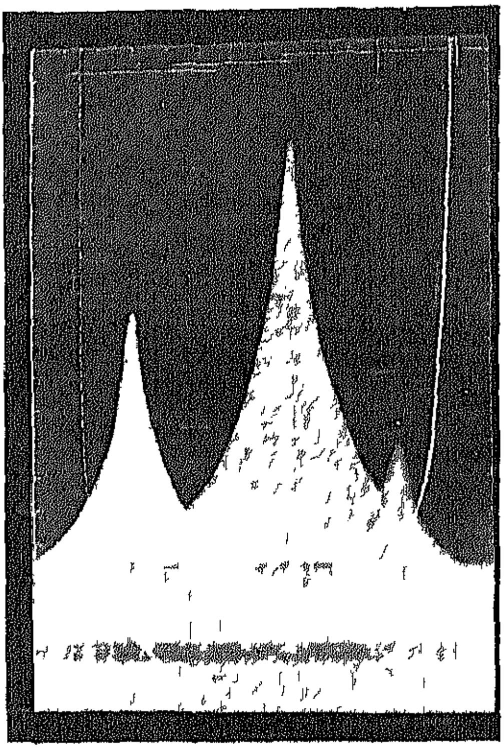

Fig.1 Density and temperature variation in solar atmosphere

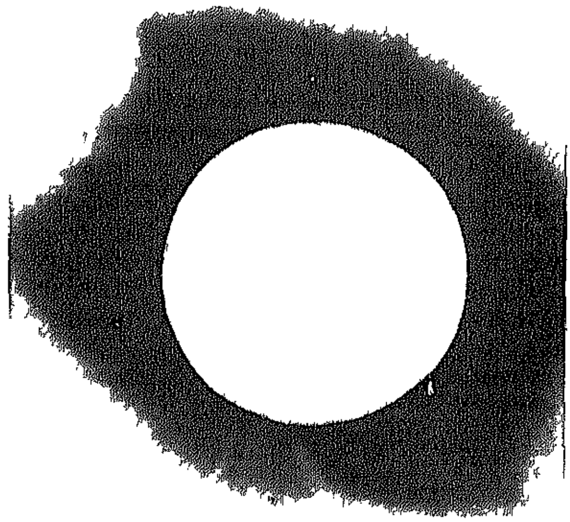

Fig.2 Total solar eclipse (Australia 1921) exhibiting solar plumes

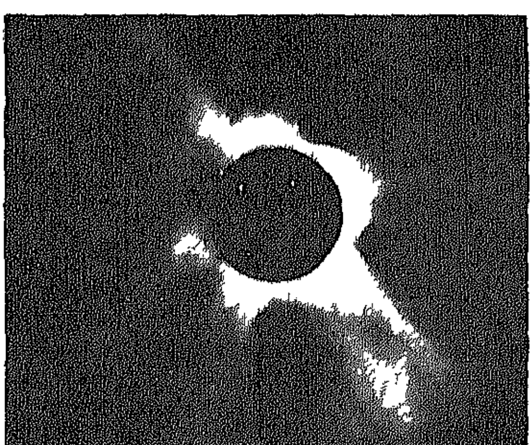

Fig.3 Total solar eclipse (Canton Island, South Pacific, 1937) A prominence named "Heliosaurus" dominates the scene

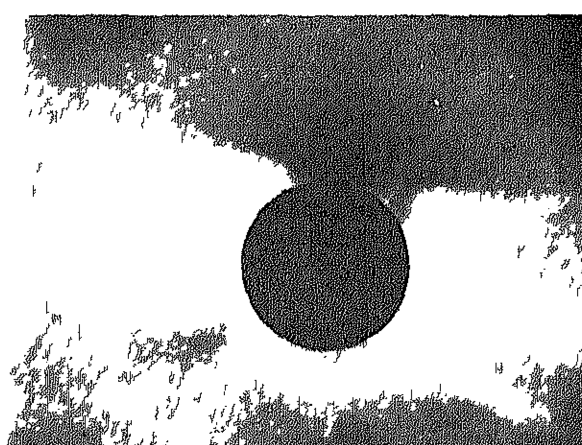

Fig.4. Total solar eclipse (East Africa 1973) Electrons patterned by magnetic fields become visible in photospheric light

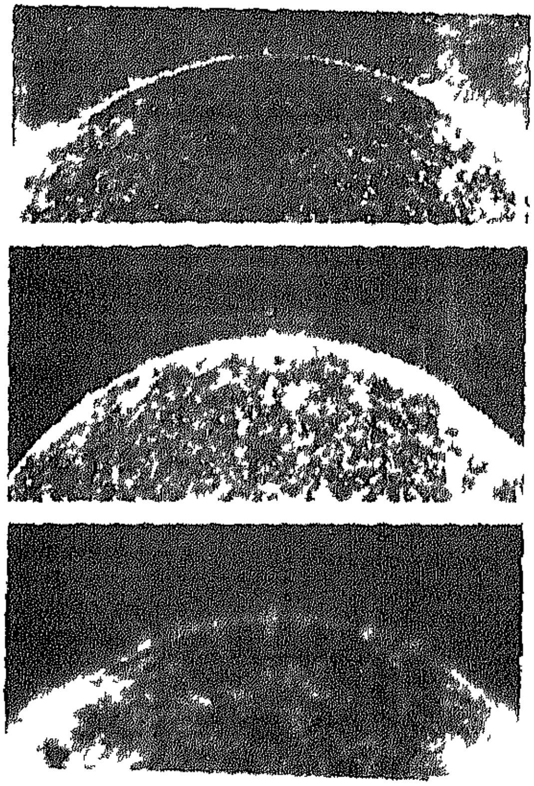

Fig.5 Polar features in coronal light Bright points are seen at the bases of polar plumes

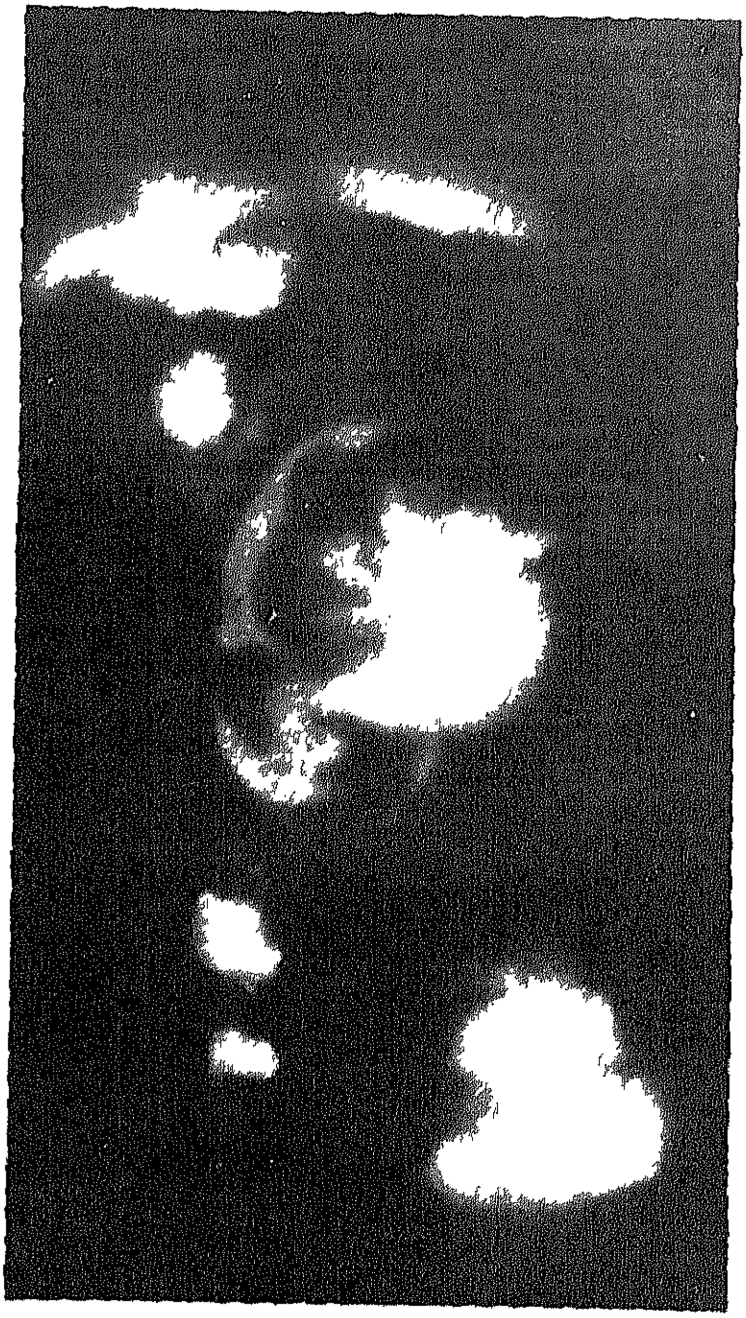

Fig.6. X rays show the hottest parts of the corona Active regions of varying brightness connect to form "Cosmic semicolon"

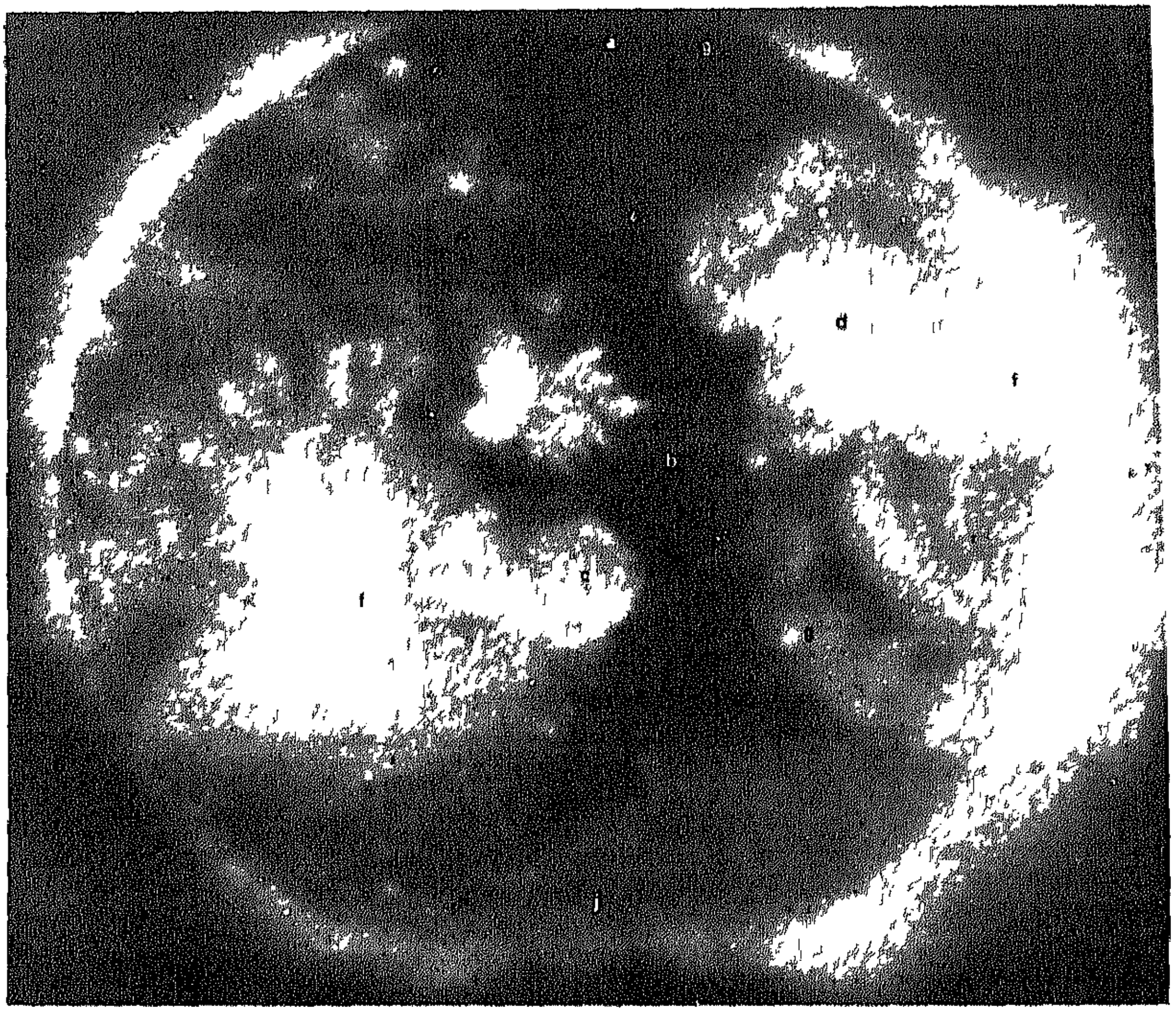

Fig.7 Absence of X rays in a coronal hole extending upto mid latitudes Tightly wound loops are the hottest regions

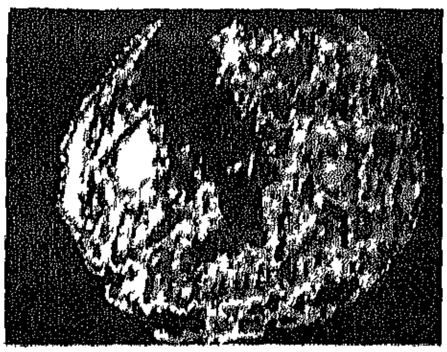

Fig.8a. A picture in ultraviolet shows the large coronal hole

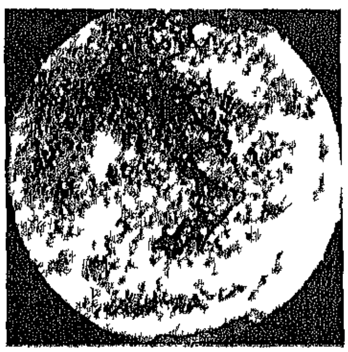

Fig.8b The Boot of Italy hole traced on a picture of high chromosphere

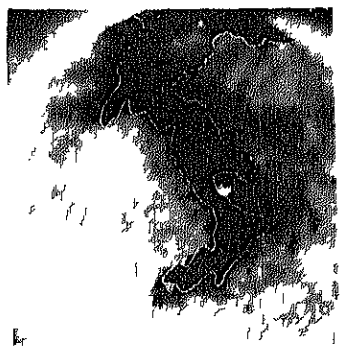

Fig.8c X ray photograph shows identical shape of the coronal hole

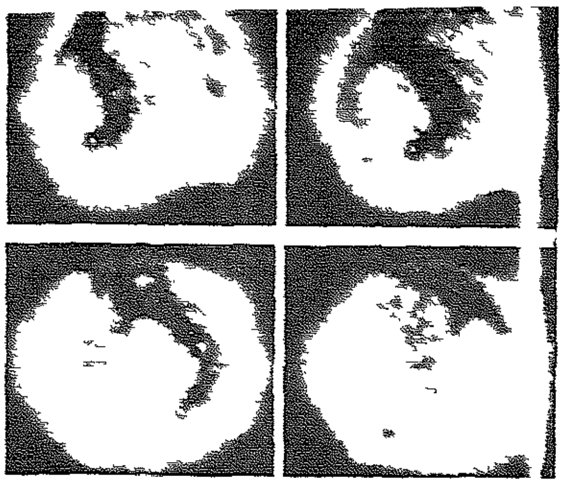

Fig.9 Rotation of coronal hole with the Sun. Pictures taken about 2 days apart

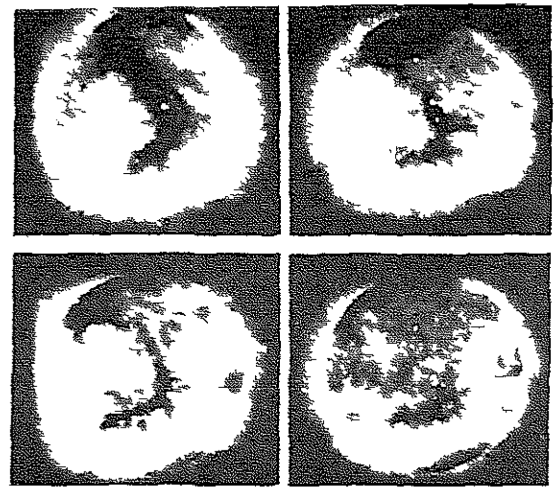

Fig.10 Soft X ray pictures taken about 27 days apart Coronal loops encroach into the hole

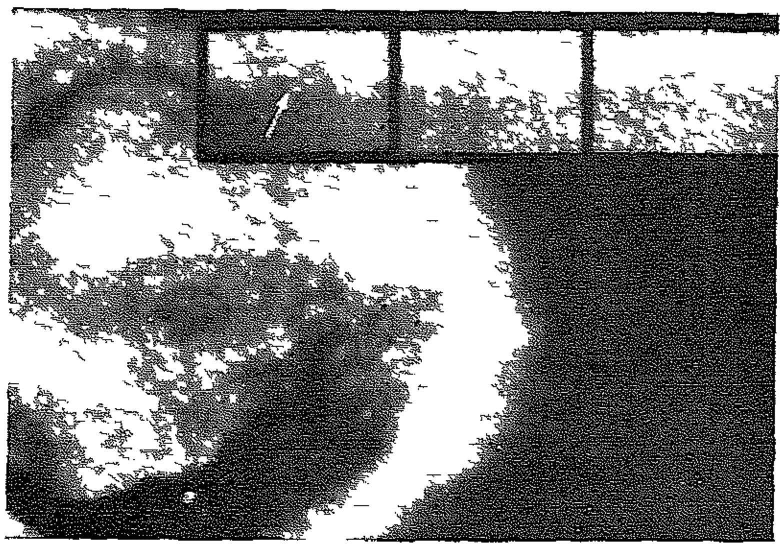

Fig.11 A pair of X rav bright points flashing alternatively off and on. The inset shows a flaring bright point at intervals of about 12 minutes

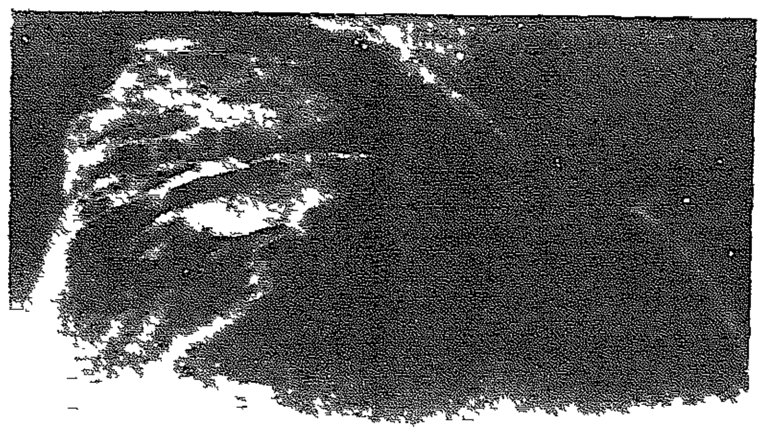

Fig.12 A huge coronal transient about 300,000 km above the Sun movisng with a speed > 00 km /sec

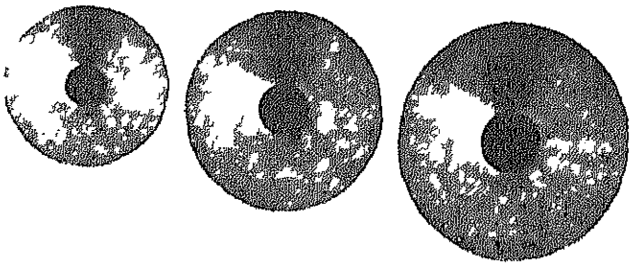

Fig.13 Rapid movement of a gargantuan disruption in the corona

Fig.14. A simultaneous image of the ultraviolet Sun showing the propeller prominence, producing the disruption in Fig (13)

radiative energy input If this energy is sufficient to overcome gravity and magnetic field, winds may result, if this energy is too large, the whole corona may be blown away The corona is highly variable and inhomogeneous, thus exhibiting the dynamical play of magnetic fields Quiet corona is a synthetic product of observational averaging over space and time

Acknowledgement

All the photographs have been reproduced from "A New Sun' The Solar Results from Skylab by John A Eddy, edited by Rein Ise, prepared by George C Marshall, Space Flight Center, NASA, Washington, D C 1979

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