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Coronal Observations and Rocket Solar Ultraviolet Results

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Observations of the extreme ultraviolet (EUV) spectrum of the sun made from outside the earth's atmosphere have enabled astronomers to supplement knowledge of the solar corona obtained by observation in the visual and near infrared region with coronagraphs. Since the solar spectrum below 500 Å arises primarily in the corona, EUV observations permit observation of the corona directly on the disk. On the basis of the knowledge of changes in the general temperature of the corona, the EUV spectrum is expected to change in the course of the solar cycle. Some short-term changes already have been observed at the time of solar flares. Particularly large effects are found in the near x-ray region. Observations of the EUV spectrum, combined with ground based observation give new information on the structure of the chromosphere-corona transition zone.

OBSERVATION of the extreme ultraviolet (EUV) spectrum of the sun from rockets and satellites is a unique example of the way in which rocket vehicles may extend and supplement knowledge obtained by conventional means. The solar corona has been under observation for a number of years. It may be seen at the time of total solar eclipses, or it may be studied with special coronagraphs placed on mountaintops. However, in any event, observation is always limited to the region between about 3300 and 11,000 Å. In fact, outside the easily accessible visual region, only the strongest features may be seen.

The temperature of the solar corona is very high, between 1 and 2×10^6 deg; consequently, all the atoms are in highly ionized states. The permitted spectrum lines of such highly ionized ions all lie in the extreme ultraviolet and therefore may be observed from above the earth's atmosphere. However, a few ions have ground states that are split by spin-orbit interaction, so that it is possible to observe spectrum lines corresponding to electron jumps between these lowest levels. This is the only reason that line radiation can be observed from the corona in the visual region of the spectrum at all. Notable among the ions observed are FeX through FeXV (with the exception of FeXII), CaXII, CaXIII, and CaXV and ions of argon and nickel. (In the standard terminology, FeX means an iron ion with 9 electrons removed.) The coronal lines of FeX and FeXIV, commonly known as the red and green coronal lines, have been observed regularly at mountain observatories in Switzerland, the Pyrenees, and Colorado since 1940. Since the end of the war a number of other coronagraphs have been put into operation in various countries.

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Coronagraphic observation of the corona has several disadvantages and limitations. The principal one is the fact that the corona may be seen only at the edge of the sun. The forbidden lines in the visual region are so weak that it would be impossible to see them against the bright line of the sun. Thus one only may hypothesize the behavior of the corona between the time it is observed on one limb and the time it is seen on the other limb of the sun. Since the sun rotates once in 27 days, there is a period of 10 or 11 days when a region on the sun is facing earth but may not be observed by the coronagraph. The permitted lines of the coronal ions in the extreme ultraviolet region, however, are very easy to see; in fact with a few exceptions they are the only lines visible in that portion of the spectrum. This is because the solar photosphere has a color temperature of only 6000° and its radiation falls away very sharply in the ultraviolet. The remaining principal source of radiation in the EUV is the solar corona. It should be pointed out that the coronal regions do not change very much in the course of 10 or 11 days, and usually a region that is seen to come onto the sun at the east limb will rotate off at the west limb without great changes. However, there are short-term variations that are important to observe. Thus, the EUV observation of the sun gives the effect of a coronagraph working on the solar disk as well. It should be pointed out that this also is achieved by radio astronomical observations, which give additional information on the corona on the disk.

The relative intensity of the lines of different states of ionization gives a very simple means of determining the temperature and degree of excitation in various coronal regions.[1] The ionization potential necessary to produce the red line of FeX is 250 v, for the green line of FeXIV, 350 v, and for the yellow line of CaXV, 814 v are needed. The variation of the distribution of these lines through a solar cycle depends on both temperature and density. At solar minimum the red and green lines are approximately equal, and both very weak. When sunspots appear, the corona above each sunspot is seen to be much brighter; this increase appears chiefly in the radiation of the green line. The corona above a sunspot is therefore at a higher temperature and a much higher density than the "quiet" corona. As the sunspots increase in number and size, the sun becomes fairly uniformly covered by this higher density and higher temperature corona. Thus the solar corona is connected intimately with the sunspot cycle and the phenomenon of solar activity itself. Most of this activity is essentially invisible in the normal spectrum. It only may be seen with very specialized instruments such as coronagraphs or observed in the radio emission of the sun. However, since the radiation in the extreme ultraviolet comes almost exclusively from the corona, there are large changes in this radiation with the variation of solar activity.

Normally the ultraviolet solar radiation, as it is known from observations by the various groups working in this field,[2-4] shows lines of ions of about the same ionization potential as those seen in the visual region. Figure 1 shows the EUV spectrum as recorded by Hinteregger and co-workers.[4] Strong permitted lines of OVI, NeVIII, MgX, and SiXII are seen. There are, however, somewhat higher ionization lines of FeXV and FeXVI, which are also quite strong. One would expect that, as the relative intensity of the lower and higher ionization coronal lines varies with sunspot cycle, the same variation should be observed in the emission lines of the extreme ultraviolet. Present observations are not yet sufficient to confirm this.

Coronagraph observations of solar flares that occur on the limb of the sun have shown that at the time of the flare there is a great increase in the density of the corona directly above the flare. Figure 2 shows a spectrogram obtained at the climax of such an event. The normal density of the corona just above the surface of the sun is about 10^9 atoms/cm^3. Above a very active sunspot this rises to 5 or 6×10^9, but at the time of the flare densities as high as 10^{11} protons/cm^3 have been observed. At the same time, the temperature apparently also increases greatly. The yellow coronal line of CaXV, which has an ionization potential of over 800 v and is characterized by temperatures of about 4×10^6 deg, commonly is seen above very active sunspots. At the time of a flare, however, this line is increased very greatly in intensity. It is not known now how high the temperature goes, because there may be material at a higher temperature which does not radiate even this high excitation line; but it certainly is known that at least a part of the phenomenon called a solar flare is a great increase in the temperature and density of the corona. Observations of solar proton storms show that a great number of high energy particles are produced very suddenly in the flare region.

This evidence is well confirmed by the rocket observations in the extreme ultraviolet and near the x-ray region. Even before direct optical evidence of the coronal events associated with solar flares was available, Friedman and co-workers at the Naval Research Laboratory[5] had found that there were increases in the x-ray flux in the 1 to 10 Å region accompanying solar flares. This radiation was considered responsible for the sudden short wave fadeouts occurring at the time of the flares. Further observations have shown that not only are solar flares accompanied by intensity increases in this range,

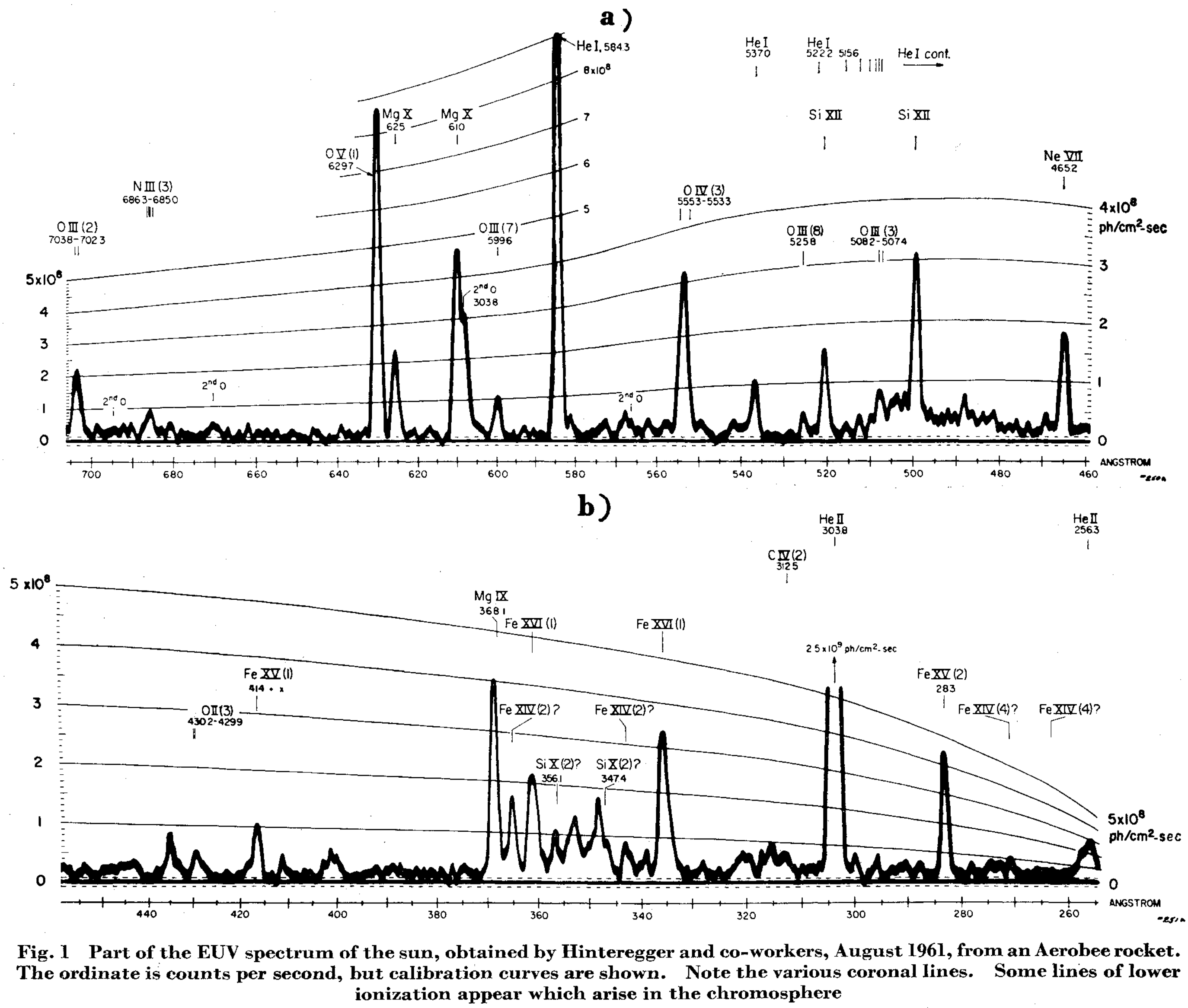

Fig. 1 Part of the EUV spectrum of the sun, obtained by Hinteregger and co-workers, August 1961, from an Aerobee rocket. The ordinate is counts per second, but calibration curves are shown. Note the various coronal lines. Some lines of lower ionization appear which arise in the chromosphere

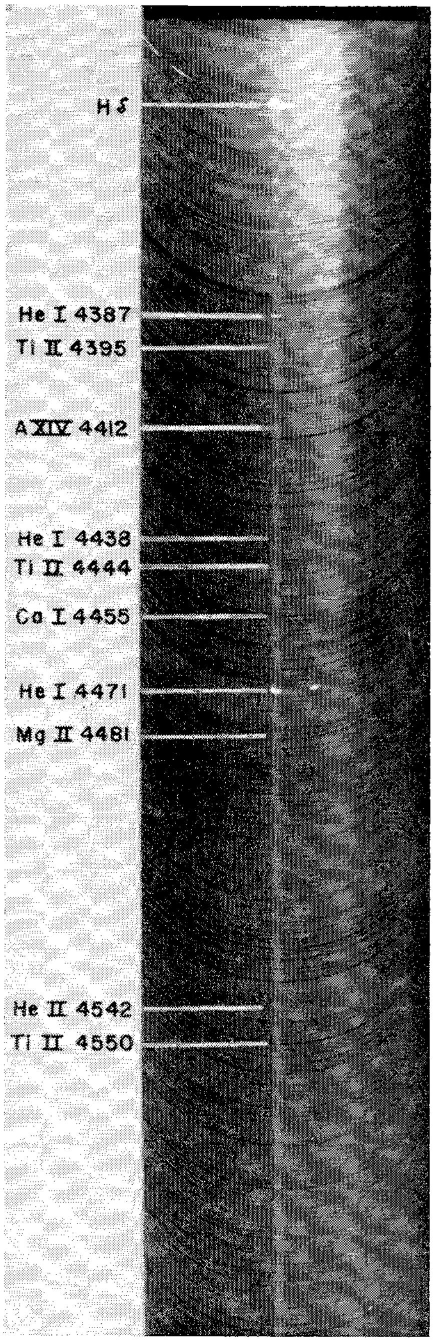

Fig. 2 Coronagraph spectrum of a solar flare, November 20, 1960. The dark absorption lines are the spectrum of the sky background. The bright streak of continuum through the center is light scattered by the hot electron gas of the flare. It is crossed by various spectrum lines including the coronal line of AXIV, which has a lower ionization potential of 700 v

but very often large active solar regions are accompanied by increases in the flux in the 8 to 20 Å region. Apparently only in the flare itself is the energy per particle high enough to give increases in the shortest wavelength region which produce ionospheric disturbances.

Because such changes can be seen in the corona only when the flares occur at the limb of the sun and are limited besides by meteorological conditions, observation of flares in this short wavelength region gives a very important new method of gaining information on the physical changes associated with all flares. In particular, optical flares are normally detected by observing with flare patrols in the light of Hydrogen-alpha. There have been cases where, possibly because the flare occurred just over the limb, there was no flare visible in Hydrogen-alpha at the time of the short wave fadeout. Coronal observations, accidentally made at the same time, have made it possible to establish that there was a great intensification in the corona which may have been responsible for the hard radiation that produced the radio fadeout. Continuous observations in the 1–20 Å regions would enable such events to be picked out without ambiguity.

At the present the study of the permitted line spectrum of he corona is just beginning. At this time the chief problem s to identify all the new emission lines found in the extreme ultraviolet. Further, the data on changes in line intensities are still sketchy. Analysis of the data in hand already has permitted solar physicists to make interesting new deductions. One of the first surprises was the great intensity of the coronal lines of FeXVI and FeXV. In the visual spectrum, the FeXIV line is the strongest observed. However, in the ultraviolet spectrum the lines of FeXIV are weak, and the lines of any of the less highly ionized stages of Fe normally observed in the solar corona are even weaker. The only ion that is observed both in the visual and in the EUV is FeXV. Now it is possible that the lines of the lower stages of ionization are not so strong as those of FeXVI and FeXV because the spectrum of the latter is concentrated in one of two very strong lines, where the others produce many lines that are harder to observe. But, one cannot escape the conclusion that there is a lot more FeXVI and FeXV than previously had been supposed. Since coronal physicists always have had difficulty in explaining why one observes so many stages of ionization to begin with, the addition of one or two more abundant stages of ionization of Fe complicates the question even further. In the last few years the level of solar activity has dropped off fairly sharply, and it is possible that unless the coronal density has fallen off too far, the concurrent cooling off of the corona will permit one to see in the EUV some of the lower stages of ionization of Fe. In any event, expect the intensity of the Fe XV and XVI lines to decrease.

The EUV spectrum also has provided us with tentative new data on the abundance of the elements. Whereas the spectrum of the lower layers of the sun is complicated greatly by radiative transfer effects and self absorption in the lines, which make it rather difficult to deduce the abundance of an element from the strength of its spectrum lines, the coronal lines are all optically thin, which means that the intensity of the line is essentially proportional to the abundance of an element multiplied by various excitation and ionization functions that also occur for the lines originating lower down. At least in the case of the corona one gets rid of some of the problems of self absorption in the lines, and it is to be hoped that after more of the fainter lines have been seen a good picture can be drawn of the relative abundance of ions of different elements in the corona, which should tell something about general cosmical abundances.

One of the most interesting tentative results of the extreme ultraviolet observations has been to confirm a previously held notion that the transition zone between the chromosphere and corona is extremely sharp. The lines of the first one or two stages of ionization of Mg and Si are seen in the visual spectrum; in fact, in the visual and near ultraviolet one may see lines of MgI and MgII and SiI, SiII, SiIII, and SiIV. In the ultraviolet, lines of MgIX and MgX and of SiXi and SiXII are seen. All, or mostly all, of the intermediate stage of ionization are missing completely. If there were a transition zone between the chromosphere, which has a temperature between 7000° and 30,000°, and the million-degree corona, one should expect to see lines of the intermediate stages of ionization. The fact that they are absent indicates that this zone is quite small in extent.

In fact, it has been thought by a number of solar physicists that material in the solar atmosphere can exist only under certain equilibrium conditions of temperature and density; and the "permitted temperatures" were about 6000, 30,000, and 1×10^6 deg. It certainly is very difficult to find lines from stages of ionization corresponding to intermediate temperatures either in the corona or in the solar flares. Even the radiation from the high temperature (30,000°) part of the chromosphere has been found to be weaker than expected. This has led to a picture of the chromosphere in which the higher temperature is limited to a great number of small jets, called spicules.

One of the most interesting satellite observations of the EUV has been the observation made by the NASA group with a spectrometer on the orbiting solar observatory.[6] They find that the intensities of some of the EUV lines, in particular the resonance lines of FeXVI, increase sharply at the time of a solar flare. Since this instrument looks at the whole sun, while the flare only covers a small fraction of the sun, the increase in the flare region really must be very large. It will be extremely interesting to compare optical observations of the flare spectrum with the data from the orbiting solar observatory.

I have tried to give a general outline of coronal problems which may be studied simultaneously from the ground and from above the atmosphere. It is to be hoped that this study will prove a fruitful source of new knowledge about the solar atmosphere.

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JUNE 1963 AIAA JOURNAL VOL. 1, NO. 6

Instabilities in a Coaxial Plasma Gun

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Configuration instabilities have been observed in a gas triggered coaxial plasma gun. Probe measurements of the azimuthal component B_θ and axial component B_z of the magnetic field indicate that the current distribution is initially azimuthally symmetric but collapses into a spoke, at a time close to current maximum. Optical data, taken with a Kerr cell camera, confirm this observation. The instability is found to depend on the gas distribution in the gun at the instant of firing and can be avoided by "tailoring" the gas density profile.

Introduction

THE radial current sheet in a coaxial gun is hydromagnetically unstable against sweeping up into a single spoke or pinch on one side of the barrel. One hopes to operate such a device in a manner that will not allow this instability to grow to disastrous proportions before the acceleration is complete. The fatal attributes of such a spoke are that 1) it sweeps up very little of the gas that uniformly fills the barrel cross section and 2) it develops very violent secondary instabilities of its own which consume large amounts of energy in driving the randomly directed fluctuations.

An experimental study of a gas triggered coaxial plasma gun is presented in which two operating modes are obtained, depending on the pressure distribution in the gun at the instant of firing. One mode is characterized by a uniform current sheet propagating along the axis of the gun at velocities $\sim 10^7$ cm/sec; the current distribution in the alternate mode is initially symmetric but subsequently collapses into a spoke in a time short compared to the acceleration period. This spoke is observed with magnetic probes, measuring the azimuthal component B_θ and the axial component B_z of the magnetic field, and with a Kerr cell camera. A detailed discussion on the propagation of the uniform current sheet is presented in Ref. 1. Observations on the unstable mode are presented in this report, together with a brief description of the plasma gun.

Description of the Gun

The general arrangement of the gun and typical operating conditions are shown in Fig. 1. Ten low inductance ca-

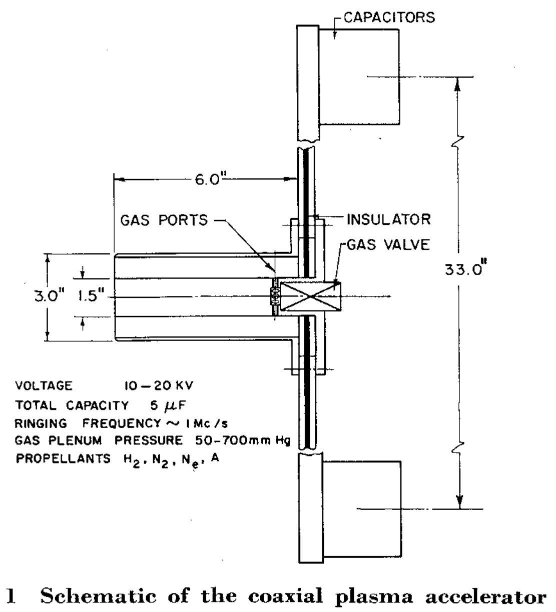

Fig. 1 Schematic of the coaxial plasma accelerator

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