CORONAL MASS EJECTIONS

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Abstract

This paper gives a brief review of current observation, interpretation and theory of coronal transient mass ejections. Some recent new results are described.

1. Introduction

The Sun ejects coronal mass in sporadic highly time-dependent events. As they move through the corona, these ejections can be observed in Thompson-scattered light, using coronagraphs. Since the early seventies, four coronagraphs have been flown in space to observe coronal mass ejections. They are the coronagraphs on the satellites OSO-7 (1971-1974, 3-10 $R_\odot$), Sky Lab (1973-1974, 1.6-6 $R_\odot$), P-78 (1979-1985, 2.6-10 $R_\odot$), and Solar Maximum Mission (since 1980, 1.5-6 $R_\odot$), with their lifetimes and fields of view as indicated. Rapid changes in the corona were not identified until these coronagraphs were flown. There are two reasons. First, it is necessary to get above the earth's atmosphere to detect the weak signals from the corona above 2 $R_\odot$. Second, time resolution of a fraction of an hour is needed to observe temporal changes. Now that we know mass ejections are there, even ground-based coronagraphs can be used to look for them. The High Altitude Observatory has one in Hawaii with its field of view limited to about 2 $R_\odot$ from the limb, complementing the fields of view of space-born coronagraphs covering the dimmer outer corona. This instrument has been able to observe about 60 mass ejections since observation began in 1980. A wealth of data now exists, spanning more than a full eleven-year solar cycle since 1973. In the following, we describe briefly the observed properties of mass ejections and major issues in interpretation and theory; see also MacQueen (1980), Dryer (1982), Hundhausen et al. (1983), Wagner (1984), Rosner, Low and Holzer (1985), and Hildner et al. (1986).

2. Observed Properties and Physical Implications

Much of what we know about mass ejections comes from photographs taken with a coronagraph. We should always bear in mind that the

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ejections are three-dimensional objects seen in optically thin Thompson-scattered light in projection on the two-dimensional images. The projected features in mass ejections commonly appear in the form of loops. One-third of the mass ejections from the Sky Lab data are loop-like, whereas more than half from the Solar Maximum Mission (SMM) data are loop-like. In later epoch, loop-like mass ejections tend to come with a three-part structure - a leading bright loop, a trailing dark cavity, and a bright center. The bright center is often identifiable as material from an erupted prominence. The total mass in an ejection has been estimated to be $10^{15} - 10^{16}$ grams. The apparent speeds obtained by tracking the leading edges of loops have a broad range, from below 100 km s^{-1} to nearly 1000 km s^{-1}. Typically, the sum of kinetic and gravitational potential energy is about 10^{31} erg, which is comparable to the energy of a flare. Magnetic fields cannot be measured directly but there are suggestions that magnetic forces drive the mass ejection.

It is interesting the speeds of mass ejections are often not higher than they are found to be. In the low corona, the sound speed of a $2 \times 10^{6\,\circ}$ corona is about 200 km s^{-1}, the Alfven speed is about 500 km s^{-1} for a moderate magnetic field and the gravitational escape speed is about 400 km s^{-1}. The SMM data show that the average speed of leading edges of loop-like mass ejections is about 350 km s^{-1} during the solar maximum of 1980 but only about 100 km s^{-1} as we approach solar minimum in 1984 (Hundhausen 1986). These average speeds are below the Alfven and gravitational speeds. In fact, two-thirds of the mass ejections observed in 1984 move at less than 100 km s^{-1}, well below the sonic speed. Moreover, the leading edge tends to move with only minor acceleration or deceleration. Evidently, the mass ejection is subject to a force that nearly balances out the gravitational force.

The rate of occurrence is interesting. Near solar minimum in 1973, it was a little less than one per day. The SMM data show a similar rate at the 1980 solar maximum and a dramatically decreased rate of .2 per day at the present approach to another solar minimum (Hundhausen 1986). The P-78 data show a higher rate for the solar maximum of 1980, about 1.5 per day, but agrees with the rate of .2 per day for 1984 (Sheeley 1986). The discrepancy for the rates for 1980 needs to be resolved. Mass ejections evolve in form as they move out. The difference in fields of view and spatial resolutions of the observing instruments may be at the root of the discrepancy. In any case, there appears to be a variation of the rate with solar cycle but that variation does not appear to be a simple proportionality to sunspot numbers. Given these rates, the mass loss to the Sun due to the mass ejections is not more than five percent of the solar wind loss. Mass ejections are not important as a mass loss mechanism but its indirect influence may be important if they, in fact, open up magnetic fields to allow the flow of the solar wind.

A little more than half the mass ejections are not associated with concurrent chromospheric activity. This is not surprising because the associated activity may lie behind the limb. For those associated with chromospheric activity on the front side of the limb, there is strong association with flares and even stronger association with prominence-eruptions without flares. Prominence eruptions and flares often go together. The association is then highest with prominence eruptions that occur with or without flares. This association pattern was first found in the Sky Lab data and is essentially unchanged for the SMM events observed in 1980 (Munro et al. 1979, Sawyer 1984).

To understand the phenomenon of mass ejections, there are three broad questions to answer. Under what circumstance and by what mechanism can a mass ejection be initiated? What is the dynamics of the propulsion through the corona? What is the fate of the mass ejection in interplanetary space? The last question has only recently begun to be resolved and much of the preoccupation so far has been with the first two questions. To answer these questions, an MHD fluid description is a reasonable first approximation, given the usual length and time scales of interest. Unfortunately, the MHD equations are difficult to treat. The problem is difficult because of the need to deal with time-dependence, the magnetic field in multi-dimensional space and the effect of solar gravity. There are several theories attempting to explain various aspects of the mass ejection. There are two points of view which are sufficiently well based on the MHD equations and I will describe them briefly in relation to the current interpretation of the data.

The first point of view is based on extensive numerical MHD calculations (Dryer 1982). These calculations simulate the mass ejection as a finite amplitude wave with a frontal shock, which is assumed to be generated by an impulsive input of energy from a flare. Until recently, the wave was initiated in a hydrostatic atmosphere with a potential magnetic field. It was found that the energy input had to be placed in locally open magnetic fields. Otherwise, a closed magnetic field would overly restrain the ejection of mass. Recently, these simulations were criticized on the ground that quantitative comparison with observation showed important disagreements (Sime, MacQueen and Hundhausen 1984, 1985, Dryer and Wu 1985). The simulated density structure shows maximum density enhancement at the loop top, unrestrained spreading of the loop sides, and a general absence of a trailing dark cavity. These are properties compressive waves tend to have in the open magnetic field region of the assumed ambient atmosphere. In contrast, the observed loop-like mass ejection has the maximum density enhancements at the sides, show evolution of the sides into "legs" that quickly become stationary as the loop-top moves out, and there is usually a dark cavity trailing behind the loop top. The solar corona is, of course, expanding. Steinolfson (1982) recently replaced the model having an initial hydrostatic atmosphere with one in which the magnetic field is partially open, with a solar wind flowing in the open part of the magnetic field. In the new model, the energy input can now be put in the closed field region. The global magnetic field, being partially open, does not restrain the ejection of mass as strongly as before. A loop-like structure forms with legs which do not spread out, matter being confined on the magnetic field lines that remain rooted to the

the base of the corona. The side-way propagating compressive wave fronts cannot be confined, and they continue to propagate laterally pass the legs. However, the top of the loop remains dominated by the compressive shock, giving it an unacceptably large density enhancement. The key to produce better agreement with observations is to suppress this effect of the compressive wave. This can be done by introducing heating so that higher wave speeds in the ambient atmosphere allow the compressive wave to avoid shock condition and move well ahead of the ejected matter (Steinolfson and Hundhausen 1986). The density enhancement at the loop top can then be reduced to a level below that at the legs. The important conclusion from this recent work is that the mass-ejection loop should not be identified with a wave, but is a structure moving with the frozen-in magnetic field.

Going on to broader considerations, we should realize that a large class of mass ejections are associated with prominence eruptions without flares. The need for a flare to cause a mass ejection is therefore not compelling. Moreover, even when a flare is associated, no definite cause and effect can be implied. Recently, Harrison (1986) investigated a few cases for which exist simultaneous observations from the coronagraph and the X-ray imaging instrument on the SMM. The onset of a mass ejection was found to occur not at the same time as an associated flare, but earlier to coincide with the pre-flare brightening. So, even when a flare is associated, it may not be the cause of the mass ejection. Another important point is that a majority of the mass ejections have speeds way below the characteristic wave speeds (e.g., below 100 km s^{-1}). The impulsive-energy model cannot produce this kind of mass ejections because the impulsive initiation naturally gives speeds typically of the order of the wave speeds in the ambient medium. What makes the matter so complex and interesting is that the density structures of fast and slow mass ejections are not qualitatively distinguishable.

This brings us to another point of view that others and I have advocated. Based on theoretical calculations and multi-dimensional self-similar solutions to the MHD equations, the case can be argued that mass ejections need not be created dynamically, but are pre-existing coronal structures which become unstable, and break away in the general tendency of the corona to expand (e.g. Low 1982, 1985). That there should be such a tendency is hardly surprising. We already have accepted from Parker's solar wind theory that a million degree corona cannot be confined by solar gravity. If there were no magnetic fields, the corona must everywhere expand in a solar wind. Magnetic fields trap local pockets of coronal gas in approximate equilibrium by means of the magnetic tension force. But, with continual evolution and heating, eventually such local static structures break away, in a global flow with a broad range of speeds. In this view, the flare, the prominence eruption and the mass ejection, if they are associated, bear no simple relation of cause and effect, but are all consequences of a global nonequilibrium.

It is well known that the quiescent prominence often sits in a low-density cavity underneath the high density helmet structure. If we interpret the helmet structure to be a three-dimensional, high-density shell draped over the cavity, the thickness effect along a line of sight readily projects the shell into a loop-like structure. The typical three-part structure of a mass ejection, dense loop, trailing cavity, bright prominence core, then suggests that the mass ejection is this pre-existing structure breaking away, and we have a natural explanation of its common occurrence and its high association with prominence eruptions. Such a hypothesis allows us to discriminate whether the ejection loop is a planar structure or a three dimensional shell. The appearance of a long prominence arch against the plane of the sky depends crucially on the orientation of the line of sight relative to length of the prominence. If we look along the prominence, we will see it as an arch with a narrow base. If we look perpendicular to the prominence, the arch has a broad base. A similar effect of perspective obtains if the ejection loop is also an arch lying in a plane. On the other hand, if the ejection loop arises from the projection of a three-dimensional dense shell, the variation of the baselength of the loop with the orientation of the line of sight will not be conspicuous. A study by Hundhausen, MacQueen and Sime (1984), based on the SMM 1980 data, showed that, on average, the larger the arch baselength of an associated eruptive prominence, the larger is the baselength of the ejection loop. Moreover, there are cases where the arch baselength of an erupted prominence is small, signifying viewing the prominence in its plane. But, in no case is the loop baselength found to be nearly as small. This implies that the ejection loop is not likely to be a flat object in the plane of the prominence, but is consistent with a bulbous shell having an elongation parallel to the prominence.

I like to emphasize that the Sky Lab and SMM data are of a sufficiently good quality to yield rather quantitative information. Recently, MacQueen and Cole (1985) studied the time evolution of the widths of ejection loops as defined by their brightness enhancements against the background. Their analysis showed that the loop-tops generally expand as the loops moved out, but only moderately in that the width increases with the radial distance of the loop-top by a simple power significantly less than unity. It was found that the existing models, including the compressive wave model and the self-similar solutions, cannot reproduce this quantitative behavior of the loop width. In each case, the model predicts a broadening with a power index greater than unity.

3. Conclusion

Let me point out a few prospects for the future. There is need to compare the different data sets and resolve discrepancies such as the different rates observed by the P-78 and SMM coronagraphs for the 1980 solar maximum. The fate of the mass ejection in interplanetary space is not well understood and a lot needs to be done. Interesting theoretical developments can be expected, to explore a variety of ideas and to test them with observation. From a general astrophysical point of view, coronal mass ejections are one of many examples of a common phenomenon in which a magnetized plasma is expelled out of a gravitational well. In the case of the coronal mass ejections, the proximity of the Sun makes it possible to gather a wealth of information about them, and the prospect is there to raise and address interesting questions having a depth not usually possible in other areas of astrophysics.

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