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Correlations between CME Associated Flare Magnitude and *in situ* Quantities

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Abstract. We describe a study of the compositional properties of heliospheric ICME ejecta within the context of solar CME observations. In this study, we examine CME-ICME pairs with an associated flare. For each of these pairs several in situ quantities are averaged over the event and compared with flare magnitude. We find that Mg/O, He/O, and He/H are clearly correlated with flare magnitude suggesting that larger flares provide the CMEs with increased access to the low corona. We also find flare magnitude is positively correlated with velocity and negatively correlated with density, indicating that CMEs which are related to large flares are more likely to experience over-expansion during their propagation to 1 AU.

Keywords. Sun:abundances, Sun:CMEs, Sun:flares, Sun:solar wind

1. Introduction

Coronal mass ejections (CMEs) were first discovered in the 1970s (Tousey 1973) by remote sensing instruments aboard the SOLWIND spacecraft. Interplanetary CMEs (ICMEs) had been observed prior to this, but were thought to consist of flare ejecta, a misconception that prevailed for some time after CMEs were first observed (Gosling 1993). Today the detailed connection between ICMEs and CMEs and the degree to which flares affect this connection are still not well understood. Currently there are spacecraft observing the Sun by means of both remote solar imaging and in situ solar wind observations. Providing a link between these two types of data sets is essential to understanding the processes that cause CMEs.

Reinard 2005a (hereafter referred to as Paper1) investigated the relationship between heliospheric charge state and flare association for 67 CMEs. Charge states provide an in situ measurement of coronal temperatures at the solar source region (Henke *et al.* 1998) and so an association between the hot flare plasma and enhanced charge states was hypothesized. It was found that for the 43 events with flares originating in central regions (defined as 30E<x<45W) the charge state ratio had a moderate correlation with the flare magnitude (i.e. larger flares were associated with larger in situ charge states). This correlation suggests that hot ions from the flare enter and/or heat the CME plasma. In this paper we build on that framework and consider how other in situ quantities relate to flare magnitude. A description of how the events were chosen and analyzed can be found in Paper1. CME-ICME pairs were identified by Cane and Richardson (2003). CMEs were identified with the SOHO/LASCO (Large Angle and Spectrometric COronograph) instrument (Brueckner *et al.* 1995). In situ data were obtained from the ACE (Advanced Composition Explorer) spacecraft (http://www.srl.caltech.edu/ACE/ASC/). Flare identification was made using the Solar Geophysical Data reports on the website maintained by the National Geophysical Data Center, which is run by the National Oceanic and Atmosphere Administration (ftp://ftp.ngdc.noaa.gov/STP/SOLAR_DATA/).

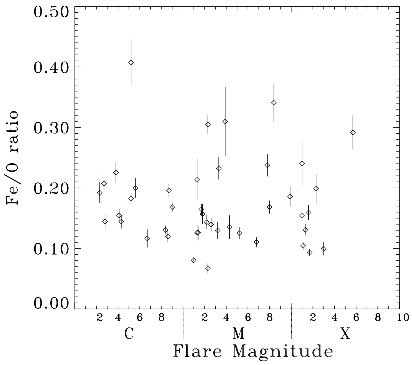

Figure 1. Fe/O is not correlated with flare magnitude

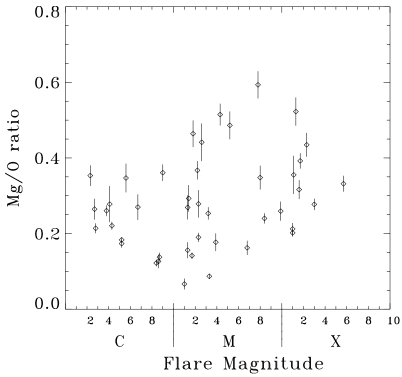

Figure 2. Mg/O is positively correlated with flare magnitude

2. Data Analysis

2.1. *Elemental composition*

In situ measurements of elemental composition reflect the coronal source region of CME ejecta. Typically, in the slow solar wind elements of low first ionization potential (FIP) such as Fe, Mg, Si are enhanced over high-FIP elements, such as Ne and He (Geiss *et al.* 1995). The solar wind is also somewhat depleted in heavy elements compared to photospheric values, because of gravitational settling in the corona. The solar wind is particularly depleted in helium (by a factor of two compared to photospheric values) because of inefficient Coulomb drag during solar wind expansion (Geiss *et al.* 1970).

To determine if elemental abundances are affected by associated flares, we take the elemental ratios Fe, Mg, Ne, and He with respect to oxygen and He/H and look at their correlations with flare magnitude. As discussed in Paper 1 we determine the statistical significance (defined as $r\sqrt{n-2}/\sqrt{1-r^2}$) of each correlation to rule out the possibility that the correlation could have occurred randomly (Larsen & Marx 1986). Conventionally, statistical significance is set at the 5% level, meaning that values above 5% are considered to be consistent with a random population. We keep in mind that this level is somewhat arbitrary. In addition, we use non-parametric, or rank-ordered, equations because of the low statistics and because the parent population may not be normally distributed. These equations reduce to parametric equations for normally distributed populations, so no information is lost by generalizing. Both parametric and nonparametric results are listed in Table 1, but in the text we only refer to the nonparametric results.

In figure 1 we plot the in situ elemental abundance ratio Fe/O versus flare magnitude for central flare events (as defined in Paper1). The vertical lines through each point are the statistical error bars, defined as $\sigma/\sqrt{n}$ where n is the number of points averaged in each event and σ is the standard deviation of the event. Clearly Fe/O is not well correlated with flare magnitude. The correlation coefficient is -0.08 and the statistical significance is 62.9%. On the other hand, Mg/O (figure 2), also a low FIP element, has a correlation coefficient of 0.33 and a statistical significance of 3.1%, which is within the 5% significance level. Ne/O (figure 3), a high FIP element, has a correlation coefficient of 0.27, and a statistical significance of 8.9%. Given the arbitrary nature of the 5% cutoff we cannot rule out the possibility that a weak correlation exists.

Turning to helium we find that He/O (figure 4) is strongly correlated with flare magnitude (r=0.40, statistical significance = 0.7%). Similarly, He/H (figure 5 has a correlation

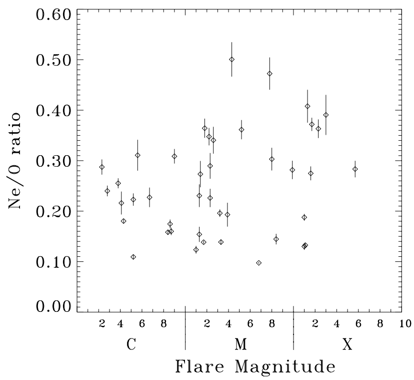

Figure 3. Ne/O has a weak positive relationship with flare magnitude

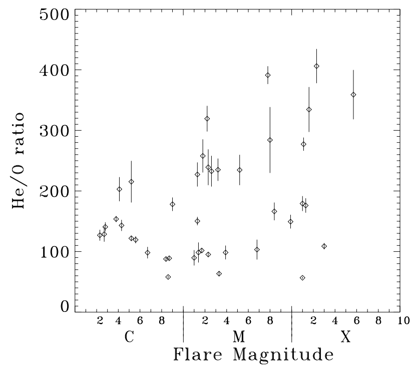

Figure 4. He/O is strongly correlated with flare magnitude

Table 1. Correlation coefficients and statistical significances for several in situ parameters as a function of flare magnitude

	# events	r_p	significance	r_{np}	significance
Fe/O	43	-0.04	82.4%	-0.08	62.9%
Mg/O	43	0.31	4.3%	0.33	3.1%
Ne/O	42	0.25	11.0%	0.27	8.9%
He/O	43	0.26	9.2%	0.40	0.7%
He/H	43	0.45	0.2%	0.49	0.07%
velocity	67	0.28	2.2%	0.24	4.9%
temperature	67	0.21	8.8%	0.135	27.3%
density	67	-0.27	2.7%	-0.35	0.3%

coefficient of 0.49, with a statistical significance of 0.07%. These results are consistent with previous studies relating helium enhancements to large flare events (Hirshberg 1971, 1972). In addition, He/H has previously been found to increase with a rising O^{+7}/O^{+6} (Reinard *et al.* 2001), so a mutual correlation with flare magnitude is not surprising.

The strong correlation between helium ratios and flare magnitude indicates that larger flares provide more access to the low corona. Heavy elements give a mixed result with Mg/O correlating well with flare magnitude, but Ne/O and Fe/O showing weak or no correlations. These results are not ordered by FIP effect, as Mg/O and Fe/O, both low FIP elements, have strikingly different correlations. Gravitational settling does not account for this effect unless Fe accumulates in deeper, inaccessible regions of the corona. However, these results are consistent with past results finding that Mg/O is well correlated with O^{+7}/O^{+6} in the solar wind (von Steiger *et al.* 1995), compared with a marginal correlation between Fe/O and O^{+7}/O^{+6} (Aellig *et al.* 1999).

2.2. *Plasma parameters*

While in situ elemental abundances are for the most part unchanged from coronal values, plasma parameters (velocity, temperature, density) are influenced during the CME expansion into the heliosphere. CME velocities tend to approach the ambient solar wind values (Lindsay *et al.* 1999), while temperatures and densities decrease due to expansion effects, particularly in large, fast CMEs (Gosling *et al.* 1994). Investigating these parameters can determine what effect flare magnitude has on CME propagation. Because plasma parameters are less localized than composition parameters (Reinard 2005b), we

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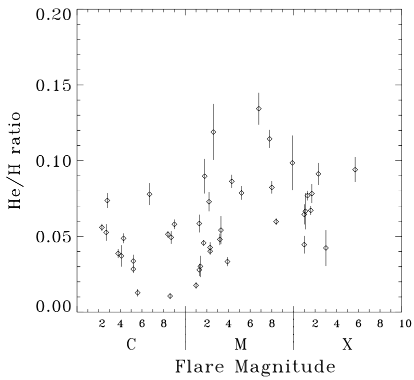

Figure 5. He/H is strongly positively correlated with flare magnitude

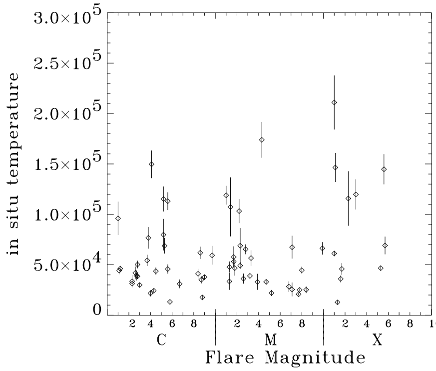

Figure 6. Temperature displays a slight positive correlation with flare magnitude.

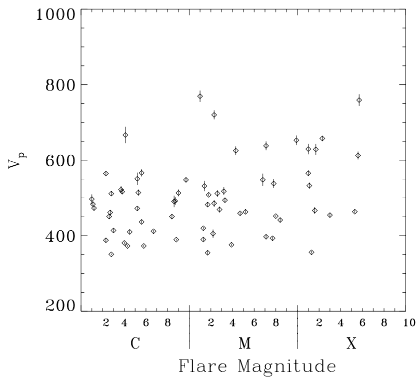

Figure 7. Velocity has a positive correlation with flare magnitude

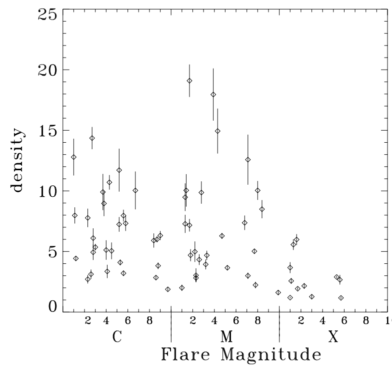

Figure 8. Density is has a strong negative correlation with flare magnitude

examine all 67 flare associated events rather than restricting our results to the central events.

Temperature (figure 6) displays a slight positive correlation, though the correlation coefficient is low (0.14) and the value is not statistically significant (27.3%). From Paper1 we would expect a higher initial temperature for larger flare events. However, Reinard *et al.* 2001 found an inverse correlation between in situ temperature and charge state. It is likely that competing effects of initial heating and subsequent expansion have an equalizing effect on the events of different initial energies.

In figure 7 we find that velocity has a positive correlation with flare magnitude (r=0.24, significance=4.9%), indicating that larger flares are associated with faster CMEs at 1 AU. This result is consistent with past studies that found that flare-associated CMEs are faster than non-flare associated CMEs (Gosling *et al.* 1974). Density (figure 8) is strongly anticorrelated with flare magnitude (r=-0.35, statistical significance=0.3%). In particular, events with a large flare association always have a low density. This result suggests that larger flares are associated with more explosive CMEs, which have a stronger overexpansion, resulting in a lower in situ density.

3. Conclusions

We present results from a study to better understand the relationship between flares, CMEs, and ICMEs. We first consider several elemental ratios. Mg/O, He/O, and He/H each correlate strongly with flare magnitude. This result indicates that large flares provide the CME with access to regions in the low corona where heavy elements are enhanced, though it is unclear why Fe/O does not follow this trend. More work needs to be done to relate these results to the conclusions from Paper1 and determine the true cause and effect nature of these correlations.

We then consider plasma parameters. We find no correlation between in situ temperature and flare magnitude. Though CMEs associated with large flares may initially have higher temperatures (given by the O^{+7}/O^{+6} ratio), these events seem more likely to overexpand and cool, which may have an equalizing effect on the in situ temperatures. Velocity is positively correlated with flare magnitude, while density is negatively correlated. We conclude that the associated flare size affects the degree to which a CME will overexpand during propagation into the heliosphere. Large flare-related CMEs are more likely to overexpand and arrive at 1 AU with higher velocities and much lower densities.

Acknowledgements

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Discussion

FORBES: The oxygen abundance ratios you use cover the range from 1-3$\times 10^6$ °K, but typical flare temperatures are in the range from 10-30$\times 10^6$ °K. Do you think that one reason why your correlation with flare size is not stronger could be that the oxygen abundance ratio reflects condition during the late phase of the flare rather than during the early impulse phase as used for determine the flare size?

REINARD: That may be a factor. Other factors causing the lower temperatures include: charge states freeze in at 2-4$R_\odot$ in the slow solar wind, and by that time the 10MK plasma may have cooled to 1MK; it could be that the flare indirectly heats the CME plasma, and may produce lower temperatures for that reason; it's also possible that the upflow jet is not as hot as the downflow reconnection jet. As far as your question, I'll try doing a comparison that includes flare length or the area under the flare curve rather than just the maximum. Using the time difference from the peak until the end may indicate whether the late phase is more important. Thanks!

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