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THE PROPER TREATMENT OF CORONAL MASS EJECTION BRIGHTNESS: A NEW METHODOLOGY AND IMPLICATIONS FOR OBSERVATIONS

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ABSTRACT

With the complement of coronagraphs and imagers in the SECCHI suite, we will follow a coronal mass ejection (CME) continuously from the Sun to Earth for the first time. The comparison, however, of the CME emission among the various instruments is not as easy as one might think. This is because the telescopes record the Thomson-scattered emission from the CME plasma, which has a rather sensitive dependence on the geometry between the observer and the scattering material. Here we describe the proper treatment of the Thomson-scattered emission, compare the CME brightness over a large range of elongation angles, and discuss the implications for existing and future white-light coronagraph observations.

Subject headings: scattering — Sun: corona — Sun: coronal mass ejections (CMEs)

Online material: color figures

1. INTRODUCTION

It is long been established that white-light emission of the corona originates by Thomson scattering of the photospheric light by coronal electrons (e.g., Minnaert 1930). Coronal mass ejections (CMEs) comprise a spectacular example of this process and are regularly recorded by ground-based and space-based coronagraphs. Thomson scattering theory is well understood and enables us to use the observed brightness of a coronal structure to estimate the number and/or the volume density of the electrons contained therein under certain assumptions (Minnaert 1930; van de Hulst 1950; Billings 1966).

In the analysis of coronal images, it is almost always assumed that the lines of sight (LOSs) to each image location are parallel to each other and to the Sun-observer (usually the Earth) line. This approximation has been used historically in the analysis of eclipse images, for which it is a reasonable approximation. When the observable emission is restricted to a few solar radii above the limb, there is very small angular divergence between LOSs through the center of the image and those lines farther away. In that case, the plane of maximum scattering, the plane of the sky, and the plane of the solar limb coincide. This is commonly referred to as the "plane-of-the-sky" assumption, and we retain the same terminology here. However, this assumption fails across extended fields of view or for observations at large distances from the Sun. On the other hand, there is no practical or computational reason to retain this assumption. Then what are the observational implications if we decide to drop this assumption, and what should we expect from the brightness of a structure observed continuously over a significant portion of an AU?

These two scientific questions become important in the interpretation of the images recorded by the Sun Earth Connection Coronal and Heliospheric Investigation (SECCHI) coronagraphs and heliospheric imagers (Howard et al. 2002) aboard the upcoming *Solar Terrestrial Relations Observatory* (*STEREO*) mission. As we show in this paper, the proper treatment of the white-light emission requires a shift in our long-established "paradigm" of the plane of the sky as the plane of maximum scattering. We start in § 2 by explaining the proper Thomson scattering geometry for solar/heliospheric observations. In § 3 we examine the range of validity of the standard plane-of-the-sky assumption and analyze some important implications resulting from dropping this assumption. We conclude in § 4.

2. THOMSON SCATTERING GEOMETRY

The theory behind Thomson scattering is well understood (Jackson 1997). Detailed treatments can be found in many papers in the literature (e.g., Minnaert 1930; van de Hulst 1950; Billings 1966). Briefly, Thomson scattering is the scattering of electromagnetic radiation (EMR) by free electrons in a plasma. The electric field component of the incident radiation accelerates the electron, which then moves in the direction of the oscillating electric field. It then reemits EMR with a direction of polarization, which lies in a plane perpendicular to the incoming EMR. The important point for our discussion is that the scattering strength for a given electron depends on the angle χ, between the LOS and the radial through the scattering electron. The angular distance between the center of the Sun and the LOS is called elongation, ϵ (Fig. 1). The scattered emission has a maximum when the LOS is at the closest approach to the Sun, namely, when the LOS is normal to the radius through the scattering electron, $\chi = 90^\circ$. That radius is called the impact radius (or distance), d (Fig. 1). The plane normal to the LOS and defined by the impact radius is commonly called the plane of the sky and corresponds to the plane of the solar limb as seen by the observer, but only when all lines of sight are assumed parallel to each other. From the observer's point of view, the polarization vector can be separated into two components, one along the direction of the incoming beam, called the radial component, and the other perpendicular to that direction, called the tangential component.

In reality, the lines of sight emanating from the observer are not parallel, and every pixel location in a coronal image corresponds to a slightly different elongation. When we trace the loci of the points where $\chi = 90^\circ$ as a function of elongation, we find that the location of the maximum scattering does not lie on a plane but on the surface of a sphere, which we call the Thomson surface (or TS for brevity). Figure 1 summarizes the proper geometry for Thomson scattering from an electron located at P, at a radial distance, r, from Sun center. The TS is centered halfway between the Sun and the observer (Fig. 1) with a diameter equal to the Sun-observer distance, R. The figure shows only a

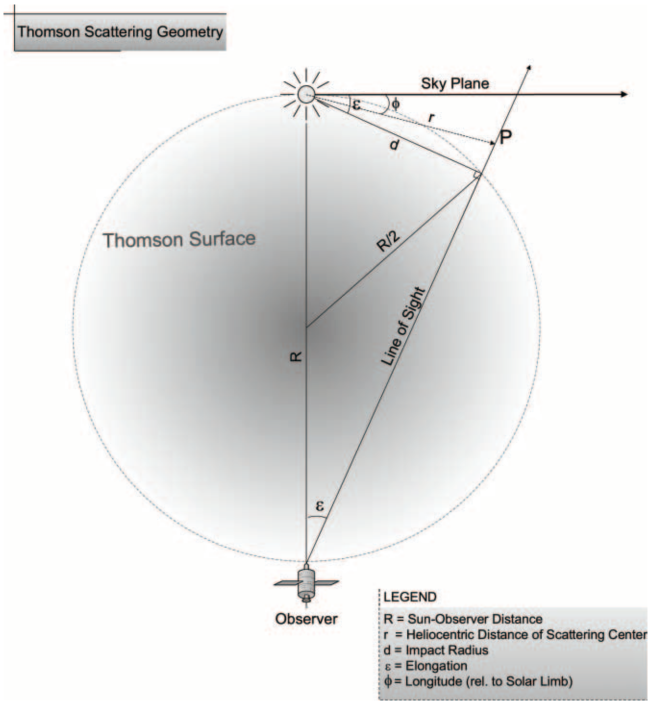

Fig. 1.— Generalized Thomson scattering geometry. [*See the electronic edition of the Journal for a color version of this figure.*]

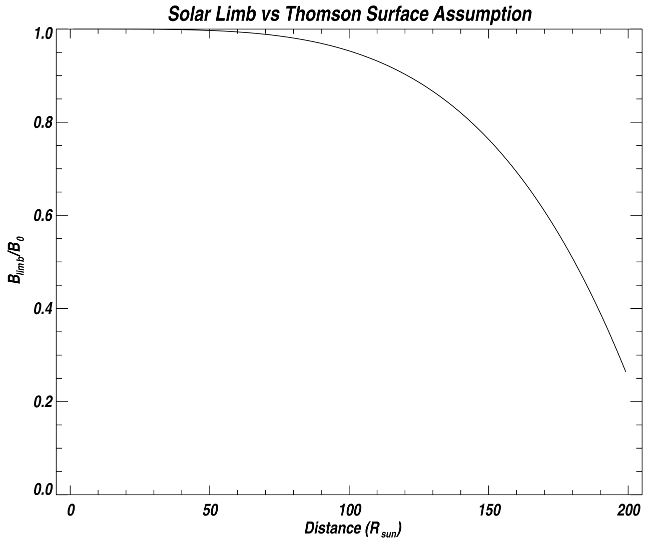

Fig. 2.— Range of validity of the plane-of-the-sky assumption currently used for CME brightness calculations. The ratio $B_{\rm limb}/B_0$ is the ratio of the brightness calculated using the assumption over the brightness derived from the full treatment.

two-dimensional projection since the situation is rotationally symmetric along the Sun-observer line.

The introduction of the concept of the TS as the location of the maximum scattering (and hence of the maximum white light emission) is the main point of our paper. The planes of the sky and of the solar limb do not play a special role in the treatment of coronagraph observations (although they are convenient approximations close to the Sun). The brightness analysis should be made relative to the TS. An obvious question concerns the implication of this proposed change in the brightness calculations in past CME analyses.

2.1. *Comparison with Standard Approximation*

The standard approximation for all CME (and streamer) brightness analyses has been to assume the plane of the solar limb to be the maximum scattering plane. We have shown that the appropriate surface should be the TS. To find the range of validity of the standard approximation we calculate the brightness of a single electron located at the limb ($B_{\rm limb}$) and the brightness of the same electron located on the TS (B_0). In Figure 2 we plot the ratio ($B_{\rm limb}/B_0$) as a function of projected heliocentric distance. The plot demonstrates that the ratio is close to 1 out to at least 70 $R_\odot$. It deviates significantly from unity only for distances close to the observer (taken at 1 AU in this case). Since almost all coronagraph analyses have been for heights below 30 $R_\odot$, the results of Figure 2 demonstrate that there is no need to reexamine past results. They also show the need to adopt the TS formalism for tracking and interpreting the CME brightness over large elongations if we want to obtain consistent results. However, this is not the only implication of adopting the TS.

2.2. *Implications for CME Observations*

A careful inspection of Figure 1 leads to two important observations: (1) The TS presents us with a changing surface of maximum scattering instead of the constant plane of the sky, and (2) the scattering geometry is not symmetric with respect to the solar limb but favors the Sun-observer side or rather the front side of the disk. We expect therefore that the brightness of a given CME will depend critically on the CME launch longitude relative to the position of the TS.

To get an appreciation for the magnitude of these effects we performed some simulations. To keep them simple, we did not address the CME structure along the LOS, which is unknown and would involve a large number of additional assumptions. Instead, our simulated CMEs consist of a single electron propagating radially away from the Sun at various angular distances from the solar limb. This simple assumption is sufficient to provide important physical insights into the CME brightness behavior and can also be quantitatively accurate. For example, we used similar simulations to estimate the degree of underestimation of Large Angle and Spectrometric Coronagraph Experiment (LASCO) mass measurements to $\lesssim$50% (Vourlidas et al. 2000). Our results were subsequently confirmed by detailed three-dimensional MHD CME simulations (Lugaz et al. 2005). Final verification for such predictions will hopefully be provided by future *STEREO* observations. Keeping the above assumptions in mind, we use, from now on, the single electron results to investigate the CME brightness.

First we examine those events originating from the front side of the Sun. In Figure 3 we plot the brightness versus elongation for a single electron propagating radially at various longitudes (the solar limb is at 0°). The plot indicates the following:

1. There is a sharp brightness falloff for all launch longitudes within the first 20–30 $R_\odot$.
2. CMEs originating at and propagating along the solar limb have a similar brightness behavior as CMEs from other longitudes up to about 100 $R_\odot$. Then their brightness decreases sharply, especially beyond 150 $R_\odot$. The obvious implication is that limb events that are bright and easily detectable by near-Sun coronagraphs, such as *Solar and Heliospheric Observatory* (*SOHO*) LASCO or SECCHI COR2, are unlikely to be detected by heliospheric imagers at large elongations.
3. CMEs originating at longitudes close to the Sun-observer line (e.g., $\gtrsim 40°$) reach a brightness plateau at around 50 $R_\odot$ or so. This plateau is almost the same for a wide range of launch longitudes and has a very shallow gradient, even for large distances

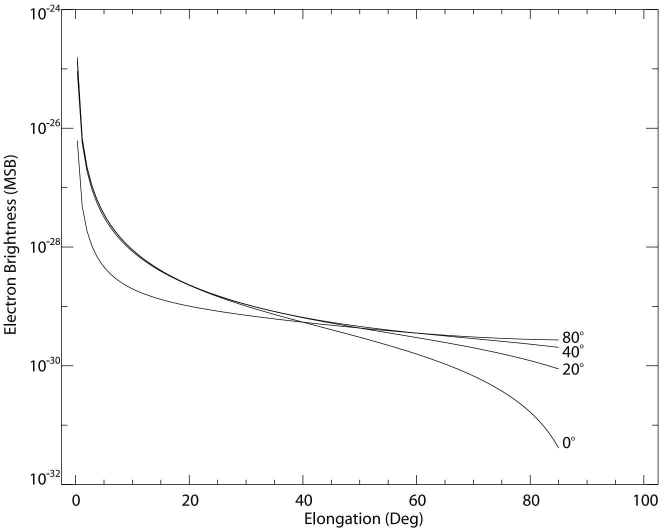

Fig. 3.—Brightness of a single electron as a function of elongation or distance for various distances from the solar limb (located at 0°). [*See the electronic edition of the Journal for a color version of this figure.*]

from the Sun. This is a surprising result, at least to us. We are unaware of any discussion of it in the literature. It implies that CMEs launched from the front disk will show very little brightness decrease through their passage from the outer corona to the heliosphere and therefore should be easily trackable with the SECCHI heliospheric imagers as long as they carry sufficient mass to be detectable in the first place. As we discussed above, this is not true for CMEs launched close to the solar limb.

Second, we looked into the front-to-back asymmetry implied by the geometry in Figure 1. In Figure 4 we plot the front-to-back brightness ratio for single-electron CMEs for various launch longitudes and for both total and polarized brightness (pB). The launch longitudes are relative to the solar limb. Each plot gives the ratio for a particular launch longitude as a function of the impact radius. We note the following:

1. Frontside CMEs are always brighter than their backside counterparts (the brightness ratio is always ≥ 1).

2. The ratio is generally very close to 1 close to the Sun, within the fields of view of current coronagraphs ($\lesssim 30\ R_\odot$). Given the broad range of CME brightnesses and the uncertainties in their electron content, the relatively small differences between frontside and backside CMEs cannot be reliably detected. Such

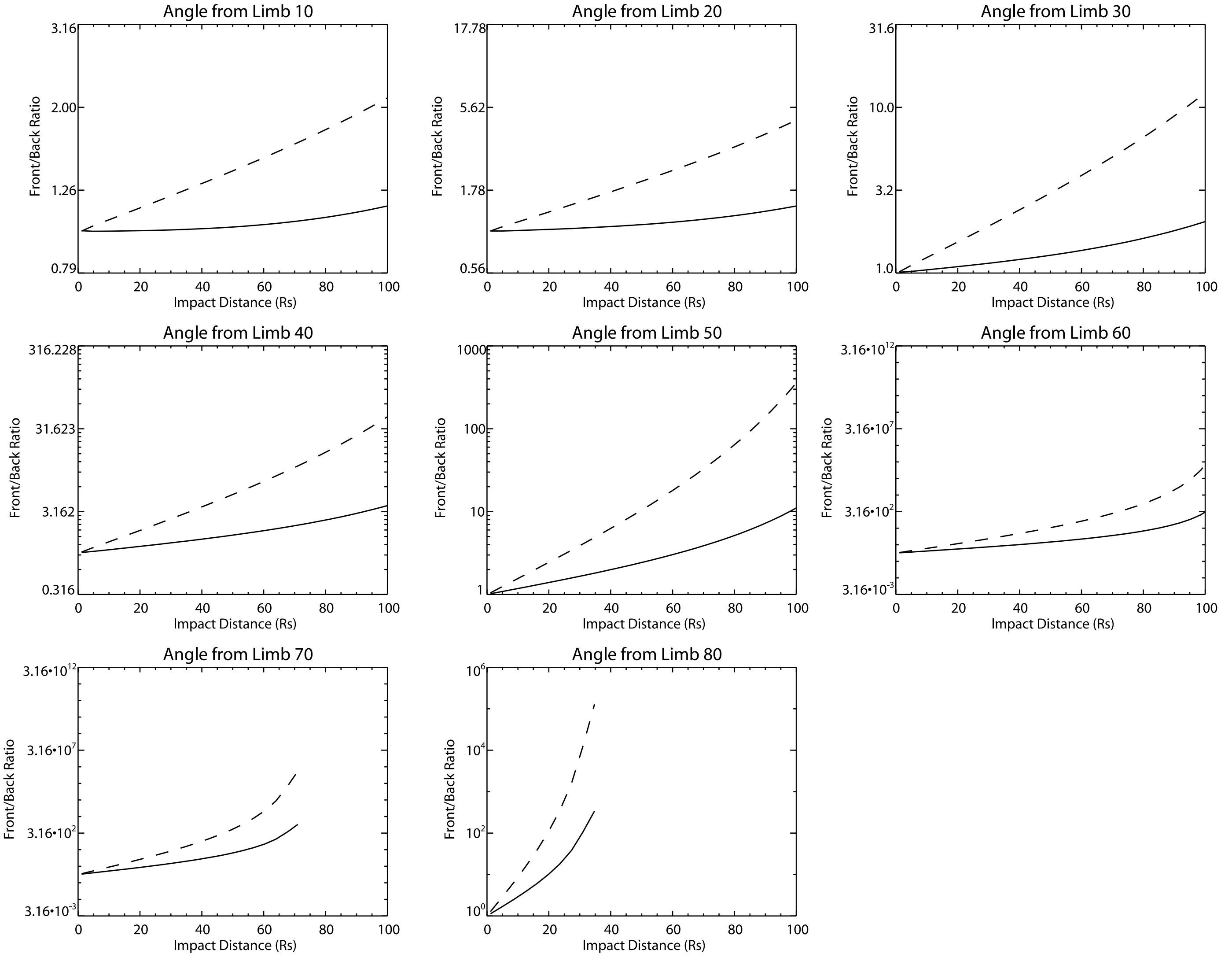

Fig. 4.—Brightness ratio between CMEs launched from the front disk and behind the limb as a function of their projected distance and launch longitude (relative to the solar limb). Both total brightness (*solid lines*) and pB ratios (*dotted lines*) are plotted.

conclusions have been reached before using the plane-of-the sky assumption (Andrews 2002).

3. There is a detectable brightness difference between frontside and backside CMEs for launch longitudes larger than 50°. This difference is particularly severe for longitudes >60°, where a very sharp transition occurs at large elongations. This is especially apparent in the pB curves. These results imply that backside events originating close to the central meridian should not be easily detectable by coronagraphs. This is contrary to the prevailing assumption in the field, that front and backside halos are undistinguishable. The brightness curves also suggest that backside CMEs will tend to fade faster with height than frontside events. This phenomenon might be a possible explanation for a number of events seen to disappear midway through the LASCO/C3 field of view (Vourlidas & Howard 2005). These effects would be much easier to detect in pB observations. Unfortunately, LASCO pB observations in the 20–30 $R_\odot$ range are infrequent and carry considerable uncertainties (due to the F-corona polarization). No such measurements for heliospheric imagers are available or planned in the future.

These results may directly affect the interpretation of CME observations from Solar Mass Ejection Imager (SMEI; Jackson et al. 2004), the only heliospheric imager operating currently. Based on the above discussion, SMEI is likely to observe only frontside CMEs, away from the solar limb, and especially Earth-directed CMEs. The flanks of limb CMEs could also be observed by SMEI if they extend to intermediate longitudes (say, about 40° from the limb), but the sensitivity of the SMEI photometers is probably too low to detect backside events. Analyses of specific events, currently in progress, will reveal the accuracy of these predictions.

2.3. *CME Mass Underestimation*

Because the white-light emission from CMEs is optically thin, the accuracy of measuring the total brightness of an event depends mainly on the signal detection thresholds of a given coronagraph. However, the derivation of the total electron content from brightness measurements is not so straightforward. The number of electrons in a CME or alternatively its mass is always calculated assuming that the electrons are concentrated on the plane of maximum scattering. This is really the best assumption we can make since the true extent of the CME and the three-dimensional distribution of the scattering electrons within the ejecta are unknown. The effect of this assumption on the CME masses has been discussed by Vourlidas et al. (2000) using the plane of the sky as the location of maximum scattering. It was shown that it leads to an underestimation of the total CME mass up to a factor of 2.

We repeat the same exercise here but using the TS, which is the proper maximum scattering surface. First, we calculate the brightness, B_0, of an electron on the TS as a function of elongation. Then we repeat the calculation for electrons along various angles from the limb (e.g., Fig. 3) to obtain their brightness curves, B_ϕ. The ratio B_ϕ/B_0 is a measure of the expected underestimation of the mass. In Figure 5 we show the results for a single electron CME propagating along three representative longitudes (the limb is at 0°). Since we know the longitude of our idealized CME, we know its actual mass, and we can use the inverse of those curves as mass correction factors. The curves are for frontside CMEs, but similar curves can be plotted for backside events. A few interesting observations arise from Figure 5:

1. As we have found earlier, the mass for CMEs propagating close to the solar limb is well estimated even for observations well into the heliosphere. The underestimation becomes larger than a factor of 2 only for elongations beyond about 60°.

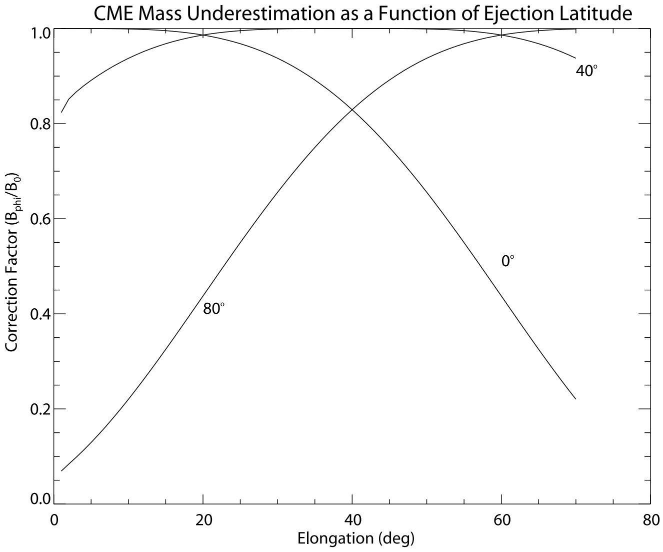

Fig. 5.—Mass underestimation curves for single electron CMEs launched at various angles from the limb (solar limb is at 0°).

2. The assumption that all electrons lie on the TS provides an excellent representation for the mass of CMEs propagating at intermediate longitudes (around ~40°). In fact, the underestimation of mass is never off by more than 20%, even for extreme elongations.

3. Halo CMEs have the opposite behavior to limb CMEs, as expected. It is interesting that estimations of their masses become more accurate at larger distances from the Sun.

3. DISCUSSION

The concept of the TS is not really new. The Thomson scattering equations have been used for years to compute electron densities from white-light brightness observations, even at large elongations (e.g., Jackson 1985). As we have shown, the historical assumptions do not lead to any significant errors. But the common observation of halo CMEs from LASCO has led to thoughts on how to provide a better mass estimate. From the analysis presented here, the paradigm of symmetry between backsided and frontsided events is not valid. CMEs with central angles far from the limb have very different behavior depending on whether they originate from the front or back side. Many LASCO CMEs are not observed beyond about 15 $R_\odot$ (Vourlidas & Howard 2005). This observation is consistent with our modeling but needs further analysis before reaching any conclusions.

The CME mass should be conserved as it propagates through the interplanetary medium. If the wrong angle is assumed for the propagation direction, the total mass will not be constant as it propagates. The curves in Figure 5 can be used to adjust the central angle of the CME until the total mass is conserved. Of course, the CME mass might increase due to material being swept up from the ambient solar wind. This would imply that a single angle cannot be found that would fit the observations. Instead, equivalent sets of curves with increasing mass pickup would need to be generated. Observing CMEs from two angles would resolve this ambiguity and would be a direct measure of mass pickup.

To test this idea, we set a simple simulation of what a CME mass analysis of SECCHI observations might provide (Fig. 6).

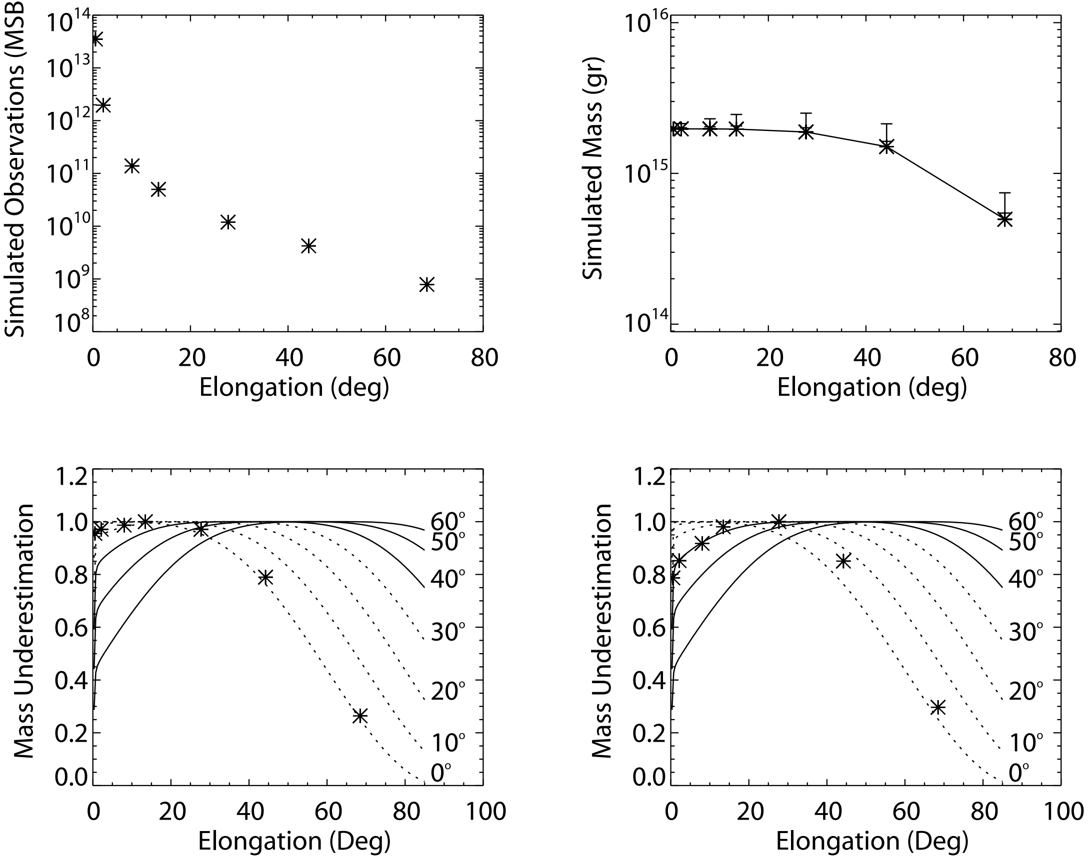

FIG. 6.—Simulation of CME observations from a single SECCHI suite. *Top left*: Total brightness of a 2×10^{15} g CME launched along the solar limb at various elongations. *Top right*: Mass measurements derived under the assumption that all electrons lie on the TS. The bar show the effect of 10% and 50% pileup on the mass. *Bottom left*: The normalized masses, for 10% pileup, are plotted on mass underestimation curves (see also Fig. 5). *Bottom right*: Same as left panel, but for a 50% pileup.

We assumed a CME of infinitesimal width, mass of 2×10^{15} g, which is launched along the solar limb. The total brightness of this CME within the SECCHI instruments' field of view is shown in the upper left panel of Figure 6. From those measurements, we calculate the mass using the default assumption that all electrons lie on the TS (stars in the top right panel of Fig. 6). We then consider the effect of mass pileup using two gradients with maximum pileup of 10% and 50% of the final mass, respectively. The corresponding pileups are shown as error bars in Figure 6. The 10% error bars are barely discernible through the star symbols in the figure. In a real analysis situation and faced with such a distribution of mass values, we would then seek to divide the masses by a correction curve (such as the ones in Fig. 5) that ideally would bring all masses to the same value (since one cannot know a priori whether pileup has occurred). But how can we find the correct curve if we do not know the launch angle of the CME?

The solution is surprising simple. In the next step, we normalize the measured masses (by the maximum mass for each of the two pileup cases). The reason for the normalization is to allow us to plot the observations directly onto mass underestimation curves (Fig. 5), which are normalized by default. The results for the two cases of pileup are shown in the lower panels of Figure 6. We see that our "measured" masses fall on or very close to one (or two) of those curves. In particular, the masses from the 10% pileup case correctly identify that our CME originates at the limb (the 0° curve), while the 50% case has a slightly higher ambiguity with the mass points falling between the 0° and 10° curves. It is obvious that we can recover some information about the launch longitude of the CME even for the high pileup case as long as observations at large elongations are available. The localization error seems to be about 10°.

These results seem to suggest that the SECCHI mass measurements might not be very sensitive to mass pileup. However, the simulations are very simple and do not take into account effects such as the three-dimensional extent of a CME and instrumental limitations. Accurate determination of the sensitivity to mass pickup will have to wait until we perform more sophisticated simulations. It is interesting to note that a mass pickup of 50% would skew the CME launch angle toward larger values if measurements at larger elongations were unavailable. This observation points to the importance of the heliospheric imagers in providing valuable constraints to the determination of the three-dimensional structure of CMEs.

Finally, we note that the studies done here are mostly for total brightness. Since there are no heliospheric pB measurements available nor are any planned for the future, we decided to concentrate on total brightness. The analysis of polarized brightness would give exactly the same behavior but would be more strongly peaked about the TS (Fig. 4).[1]

STEREO will provide a direct measure of the validity of the Thomson scattering equations. For example, there will be structures or CMEs that are observed with backside geometry from one spacecraft and with frontside geometry from the other spacecraft.

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[1] The Thomson scattering algorithm used here is available as an IDL procedure in the solar-soft library under the *SOHO* LASCO directory. The name is "eltheory.pro."

4. CONCLUSIONS

Our paper aims to bring to the attention of the community a few key issues regarding the interpretation of white-light CME observations by coronagraphs and heliospheric imagers. Our motivation is to prepare for the upcoming observations from the SECCHI coronagraphs and heliospheric imagers aboard the *STEREO* mission. These instruments will enable us to observe a CME continuously over a large range of elongations. The analysis and interpretations of these observations require a revisit of our standard assumptions and notions used so far in the field. In the previous sections, we revisited some scattering issues with a special emphasis on the proper scattering geometry. The replacement of the sky plane by the Thomson surface is not only physically correct, but it also allows us to treat the CME brightness self-consistently over arbitrary fields of view. We tried to provide a feel for the effects on this new methodology in CME brightness interpretation by performing a series of simple simulations. We recap the most important results:

1. CMEs propagating along the solar limb while bright in near-Sun coronagraphs are unlikely to be detectable further in the heliosphere.
2. Frontside events at intermediate angles will exhibit approximately constant levels of brightness over a wide range of heliocentric distances. This is contrary to our intuition, which expected events to become fainter as they travel away from the Sun. This result implies that Earth-directed CMEs are not necessarily brighter than limb CMEs, contrary to what has been previously claimed (Andrews 2002).
3. The historical sky plane assumption holds well for observations within about 100 $R_\odot$ from Sun center.
4. The adoption of the TS concept reveals an asymmetry in the scattering efficiency relative to the solar limb. It has not been noted before and suggests that coronagraph observations alone could be capable of discriminating between front and backsided events under certain conditions.
5. CME observations over a large range of elongations might allow us to estimate the CME launch angle under the assumption of mass conservation. The combined observations from both SECCHI instruments suites might allow us to determine both the launch angle and the amount of pileup during the CME propagation.

This work is concerned with the very basic effects of Thomson scattering on simple one-dimensional CMEs. An exploration of the effects of this methodology on more complex CME shapes is necessary, and we will be carrying on such an effort in the near future.

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REFERENCES

Andrews, M. D. 2002, Sol. Phys., 208, 317
Billings, D. E. 1966, A Guide to the Solar Corona (New York: Academic Press)
Howard, R. A., et al. 2002, Adv. Space Res., 29, 2017
Jackson, B. V. 1985, Sol. Phys., 100, 563
Jackson, B. V., et al. 2004, Sol. Phys., 225, 177
Jackson, J. D. 1997, Classical Electrodynamics (3rd ed.; New York: Wiley)
Lugaz, N., Manchester, W. B., IV, & Gombosi, T. I. 2005, ApJ, 627, 1019
Minnaert, M. 1930, Z. Astrophys., 1, 209
van de Hulst, H. C. 1950, Bull. Astron. Inst. Netherlands, 11, 135
Vourlidas, A., & Howard, R. A. 2005, AGU Spring Meeting, Abstract SP44A-04
Vourlidas, A., Subramanian, P., Dere, K. P., & Howard, R. A. 2000, ApJ, 534, 456