Solar Physics: Observational data analysis
Proposed by: Juan Camilo Buitrago and Santiago Vargas
75 points

The solar slap
[75 points]

Solar Cycle 25 is heating up! It began in December 2019 and will peak in 2025. The start of a new cycle means there will be increasing solar activity until roughly mid-2025. One direct consequence of such activity is the more frequent occurrence of solar flares, which are intense bursts of radiation observed near the Sun's photosphere and low-corona. Solar flares are sometimes accompanied by coronal mass ejections (CMEs), which expel coronal plasma into the interplanetary space.

We are living in a golden age for solar astrophysics. In addition to entering a period of high solar activity, we also have brand new cutting-edge solar telescopes that will allow us to study the Sun as never before. One of these telescopes is the Parker Solar Probe (ParkerSP), the first spacecraft in history to fly into the low solar corona. The ParkerSP has a somewhat eccentric orbit ($\varepsilon \approx 0.88$) and will approach the Sun as close as 7 million km (~10 solar radii) on its final orbital perihelium (in 2025). Just recently, on May 28, 2021, a C-shaped CME was detected by the NASA solar space telescope SOHO (located at a distance of 1.5×10^6 km from Earth, around the Sun-Earth L1 Lagrange point) by means of the onboard LASCO coronographs. The solar eruption generating the CME occurred at 22:19 UTC with an ecliptic traveling angle of 55º (respect to the Sun-Earth line), heading directly towards the point where ParkerSP was located. Figure 1 shows a sequence of three consecutive images made by the NASA Community Coordinated Modeling Center, highlighting the evolution of the CME for three moments, from the onset to the moment it reaches the ParkerSP.

1. [30 points]
   - Using the JHelioviewer find the CME which occurred on May 28, 2021, by using images from the Solar Dynamics Observatory (full disk) and the SOHO-spacecraft coronographs LASCO-C2 (imaging from 1.5 to 6 solar radii) and LASCO-C3 (imaging from 3.7 to 30 solar radii), as shown in Figure 2.
   - Use a selection of images to measure the distance of the CME-front from the Sun, and derive its velocity over time.
   - Use these values to construct a table dividing it in two parts (left and right).
     i. The first part of the table (left) should contain your measurements characterizing every image (including date/time).
     ii. The second part (right) should have your calculations: distance, cumulative velocity, and velocity per time interval (depending on the

number of images you are employing, for instance from first to second image, second to third, etc.).

- Do not forget to label each of the columns of your table accordingly.

2. [15 points] Make distance-time and velocity-time graphs using the measured and calculated data from your table.

3. [10 points] Considering that the CME moves at constant speed for distances larger than 30 solar radii, estimate the velocity (in km/s) of the CME front when it impacts the ParkerSP, and the time (in hours) it takes to do so from its onset.

4. [10 points] From the following statements, select the ones which are TRUE and the ones which are FALSE.

   A. A larger number of selected images would give more precise information on the evolution of the CME and the calculated physical parameters.
   B. A more precise analysis and measurements of the CME evolution should consider the differential rotation of the Sun, and therefore the calculated velocities will be affected.
   C. Any software (numerical) misalignment among the images when creating the mosaic will have direct effects on the precision of the calculations.
   D. The different assumptions made in order to construct the model displaying in a heliospheric density map in Figure 1, may affect the estimation of the Sun-ParkerSP distance.
   E. The interaction of the CME-front with the remnant dust left by the 2019 Borisov comet broadens and difuminate the images. This intensifies the lack of contrast in the images, increasing the uncertainty in determining the CME-front and its propagation.

5. [10 points] Knowing that the CME front carries a large population of protons and alpha particles, compute the expected energy (in eV) measured for a single of these types of particles, by the Solar Wind Electrons Alphas and Protons (SWEAP) instrument onboard the ParkerSP. Neglect the rest mass energy of each particle and consider the proton mass to be 1.67262×10^{-27} kg.

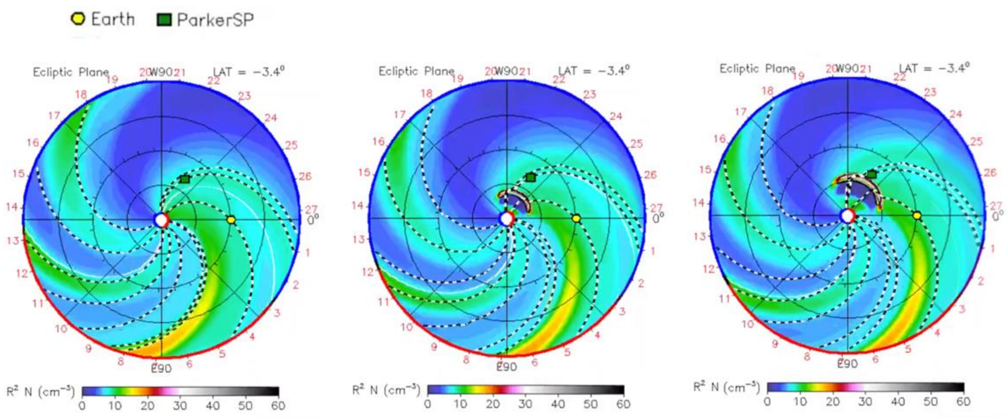


Figure 1: Sequence from NASA Community Coordinated Modeling Center displaying in a heliospheric density map, the evolution of a CME that had its onset on May 28, 2021 at 22:19 UTC.The images show the location of the Sun (center) and of Earth (at 1 AU $\approx 1.5 \times 10^8$ km from the Sun) and the spacecraft ParkerSP. Note that the CME front impacts the ParkerSP in the last image of the sequence. The angle formed by Earth-Sun-ParkerSP is 55º.

Tools: The JHelioviewer software (https://www.jhelioviewer.org/download.html) can be used to explore solar data from several solar telescopes as shown in Figure 2. Using the graphic interface you can select an observing data (Observation Date) and upload multiple solar images by adding layers (AddLayer). Using the option Jump, you can inspect a sequence of images to study the evolution of an eruptive event. By moving the cursor you get the information about the coordinates where you are located (in arcseconds) with respect to the center of the Sun (x:0” y:0”).

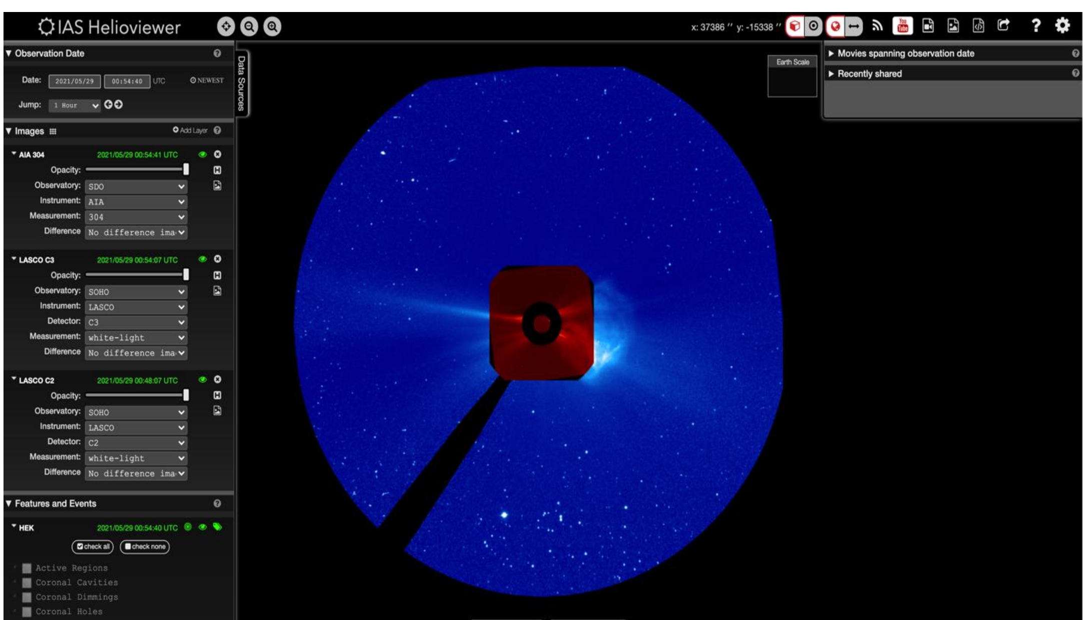


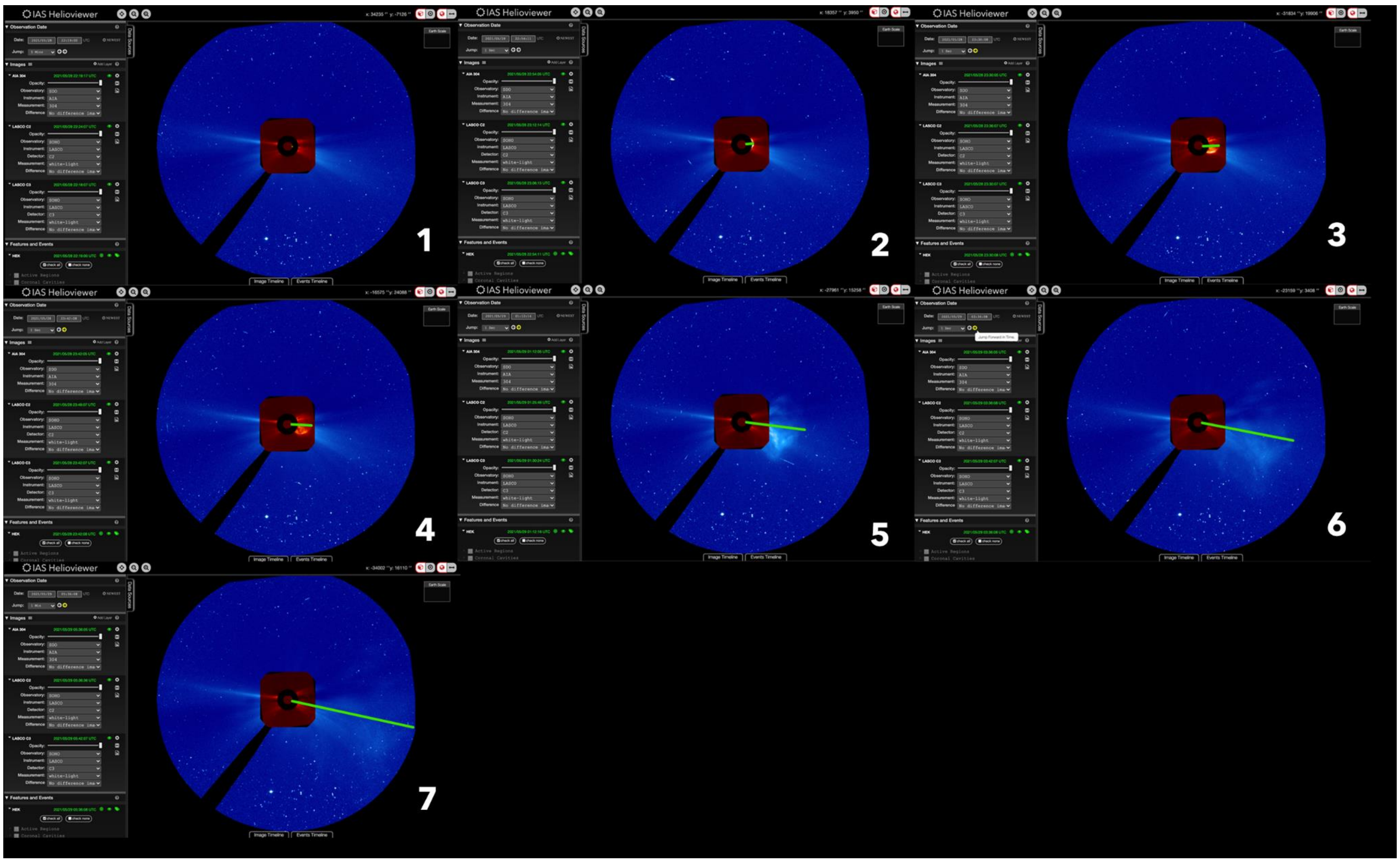
Figure 2: Exploration of solar data for May 28, 2021 with Helioviewer .

SOLUTION

PART 1 [30 points]

Section 1.1

Data selection (selecting appropriate images showing the evolution of the CME) and identification of CME front.



A total of 7 time intervals are selected tracing the evolution of the CME

1. 2021/05/28 22:19:00 UT
2. 2021/05/28 22:54:11 UT
3. 2021/05/28 23:30:08 UT
4. 2021/05/29 23:42:08 UT
5. 2021/05/29 01:12:16 UT
6. 2021/05/29 03:36:08 UT
7. 2021/05/29 05:00:08 UT

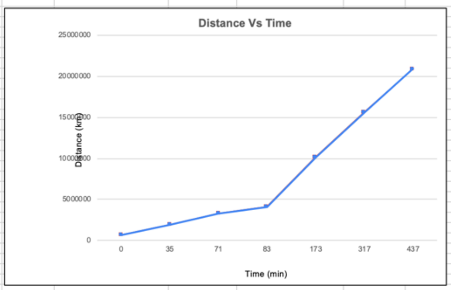
Section 1.2 and 1.3

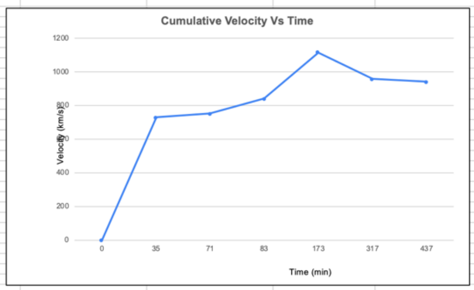
Summary of the information extracted from the images for all different selected intervals

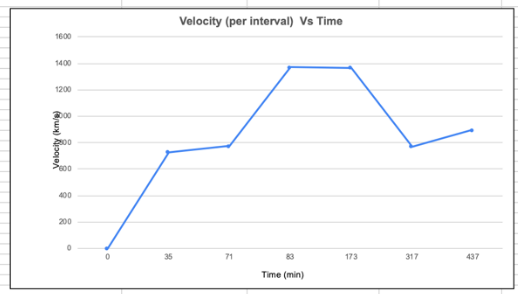
Interval	Date and Time	Time interval (minutes)	Time from CME onset (minutes)	Coordinates of the CME front x"	y"	Distance from disc center (arcsec)	Distance from disc center (km)	Distance from onset (km)	Cumulative velocity plane of the sky (km/s)	Deprojection of velociity towards ParkerSP (km/s)	Distance per time interval (km)	Velocity on plane of he sky (km/s)	Deprojection of velocity towards ParkerSP (km/s)
1	2021/05/28 22:19:00 UT	0	0	950	144	961	696617	0	0	0	0	0	0
2	2021/05/28 22:54:11 UT	35	35	2682	174	2688	1948538	1252198	596	728	1252198	596	728
3	2021/05/28 23:30:08 UT	36	71	4579	97	4580	3320520	2624180	616	752	1371982	635	775
4	2021/05/28 23:42:08 UT	12	83	5693	116	5694	4128282	3431942	689	841	807762	1122	1369
5	2021/05/29 01:12:16 UT	90	173	14000	-891	14028	10170535	9474195	913	1114	6042253	1119	1366
6	2021/05/29 03:36:08 UT	144	317	21048	-4570	21538	15615349	14919009	784	958	5444814	630	769
7	2021/05/29 05:36:08 UT	120	437	27922	-7126	28817	20892306	20195966	770	940	5276957	733	895

PART 2

Plots: distance vs time and velocity vs time constructed from the information from the previous table.







PART 3

3. Calculating the velocity of the CME front reaching ParkerSP

The velocity corresponding to the last interval (up to reaching 30 solar radii) is **895 km/s** which, according to the considerations of the problem, would be the same velocity of the CME front once it reaches the ParkerSP.

Calculating the time spent by the CME front to reach the ParkerSP from it's onset.

The Sun-ParkerSP distance estimated from Figure 1 is approx. 0.66 AU = 9.9×10^7 km = 141 solar radii (given the information that 10 solar radii es approx. 7×10^6 km)
From the previous analysis, it is known that the CME front reaches a distance of 30 solar radii after 437 minutes (7.3 hours) from its onset (see Table). The distance that the CME travels at the constant speed of 895 km/s is expressed as 141-30=111 solar radii = 7.8x 10^7 km, and thus the time spent in that interval is 42.4 hours.

Finally, the total time it takes for the CME front to reach the ParkerSP from its onset is computed as: 7.3+ 42.4 = **49.7 hours**.

PART 4. True and false statements

If we keep decreasing the time interval between successive images, the precision of measurements of the evolution of the CME and the calculated physical parameters will always keep increasing. **FALSE**
B. The analysis and measurements of the CME evolution should consider the differential rotation of the Sun, and therefore the calculated velocities will be affected. **FALSE**
C. Any software (numerical) misalignment among the images when creating the mosaic will have direct effects on the precision of your calculations. **TRUE**
D. The different assumptions made in order to construct the model displaying in a heliospheric density map in Figure 1, may affect the estimation of the Sun-ParkerSP distance. **FALSE**
E. The interaction of the CME-front with the remnant dust left by the 2019 Borisov comet broadens and difuminate the images. This substantially intensifies the lack of contrast in the images, increasing the uncertainty in determining the CME-front and its propagation. **FALSE**

PART 5. Kinetic energy calculations

Proton:
$0.5 * (1.67262x10^{-27}$ kg) * (895 km/s)^2 = 4181.2 eV

Alpha particle:
$0.5 * (6.64x10^{-27}$ kg) * (895 km/s)^2 = 16598.7 eV

Marking scheme

75 points

Section 1.1

Give A TOTAL number of points following the possible situations (select only one option):

1 points: If the table includes information extracted from **a single image (1 frame)** for date/time and the corresponding size of the CME (distance measured from the solar limb to the CME front).
2 points: If the table includes information extracted from **two images (2 frames)** for date/time and the corresponding size of the CME (distance measured from the solar limb to the CME front).
3 points: If the table includes information extracted from **three images (3 frames)** for date/time and the corresponding size of the CME (distance measured from the solar limb to the CME front).
4 points: If the table includes information extracted from **four images (4 frames)** for date/time and the corresponding size of the CME (distance measured from the solar limb to the CME front).
5 points: If the table includes information extracted from **five of more mages (5 or more frames)** for date/time and the corresponding size of the CME (distance measured from the solar limb to the CME front).

Section 1.2.

5 points. Values of distance for the number of images used.
5 points: Values of distance in km

Section 1.3

5 points: For calculating the cumulative velocity over the tabulated data

5 points: For calculating the instantaneous velocity (in every time interval) over the tabulated data.

5 points: For considering the deprojection of velocities (from the plane of the sky into the direction towards the location of the ParkerSP).

Part 2

5 points: Plotting the distance vs time for the tabulated data

5 points: Plotting the cumulative velocity vs time.

5 points: Plotting the velocities for all the different time intervals vs time.

Part 3

Velocity and time of CME front

5 points: Estimating the distance (in km) from the Sun to the ParkerSP based on Figure 1 and the appropriate unit conversions.

3 points: Considering the velocity computed for the last interval (up to 30 solar radii) that should be around 800-1000 km/s, as the velocity that impacts the ParkerSP.

2 points: Calculating the time it takes for the CME front to reach the ParkerSP from its onset (in hours), considering the time spend in the first 30 solar radii besides the time the CME is moving at constant speed (from 30 solar radii to the location of the ParkerSP).

Part 4

2 points A. FALSE
2 points B. FALSE
2 points C. TRUE
2 points D.FALSE
2 points E. FALSE

Part 5

4 points. Proton calculation

6 points. Alpha particle calculation

CONSIDERATIONS

Dear team leaders

As some of your teams experienced several troubles when fetching the images that were needed for the observational problem in solar physics, and considering the situation was completely out of our control and that was surely related to the capability of the severs and repositories where the data is stored and accessed, from either JHelioviewer or the web-based Helioviewer tools, we need to contemplate the situation to slightly adjust the evaluation process accordingly.

We aim at having all participants being evaluated under the same conditions, but in a few cases, and after not being able to get the images from the platform, we decided to provide a set of images for them to be able to start solving the questions. For this reason, the Academic Committee, for the sake of maintaining the fair principles of the Olympiads that we all promote among our teams, considers that the observational problem has to evaluate primarily the measurements that students have done over the set of images tracking the evolution of the solar CME, giving less weight to the initial part of purely selecting images.

Nonetheless, those students which spent time fetching images should receive at least some points, which won't represent a significant part of the grading, that will compensate the effort they have done for getting their set of images to start with.

In summary, we propose section 1.1 to receive 5 points (instead of 10) and section 1.2 to increase from 10 points to 15 points (being the most important part to evaluate the measurements made by the students). Section 1.3 keeps 10 points.

1.1 Using the JHelioviewer software find the CME which occurred on May 28, 2021, by using images from the Solar Dynamics Observatory (full disk) and the SOHO- spacecraft coronographs LASCO-C2 (imaging from 2 to 6 solar radii) and LASCO-C3 (imaging from 3.7 to 30 solar radii), as shown in Figure 2. **[5 points]**

1.2 Use a selection of images to measure the distance of the CME front from the Sun, and derive its velocity over time **[10 points]**

1.3 Use these values to construct a table, dividing it in two parts (left and right). • The first part of the table (left) should contain your measurements characterizing every image (including date/time). • The second part (right) should have your calculations: distance, cumulative velocity, and velocity per time interval (depending on the number of images you are employing, for instance from first to second image, second to third, etc.). **[15 points]**