The Solar Slap (75 points)

Please read the general instructions before you start this exam.

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 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 new 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 (ε≈0.88) and will approach the Sun as close as 7 million km ($\sim$10 solar radii) on its final orbital perihelion (in 2025).

Just recently, on May 28, 2021, a C-shaped CME was detected by the 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 55° (with 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 NASA, highlighting the evolution of the CME, from the onset to the moment it reaches the ParkerSP.

Assume that all spacecrafts are exactly on the ecliptic plane and the images here show a top view of the ecliptic plane.

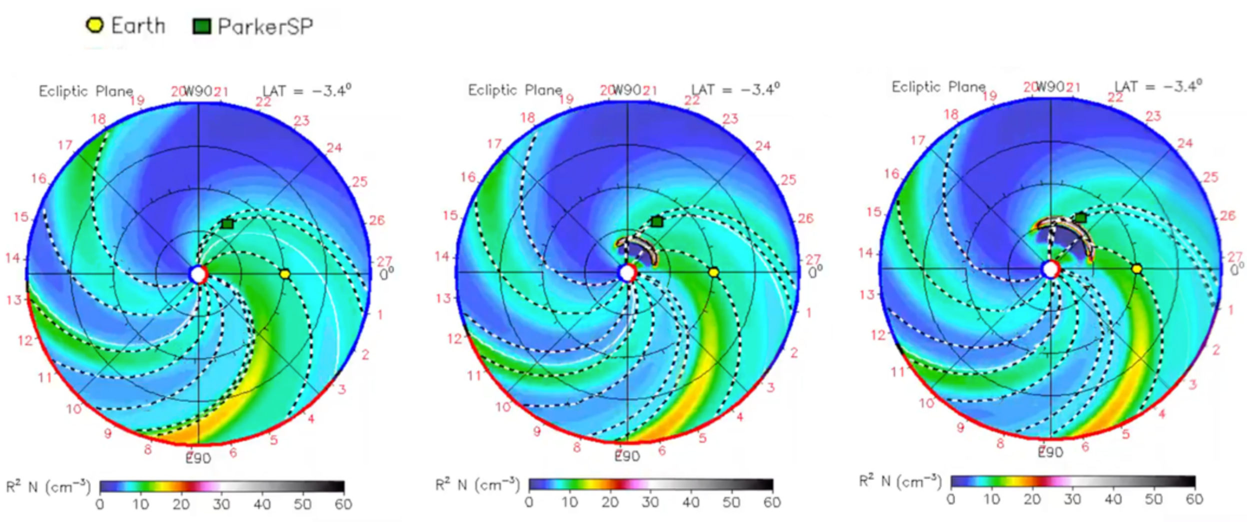

Figure 1: Sequence of images displaying on a heliospheric density map, the evolution of a CME that had its onset on May 28, 2021 at 22:19 UTC. The images show the location of the Sun (center) and of Earth (at 1 AU ≈ 1.5×10^8 km from the Sun) and the spacecraft ParkerSP. Note that the CME front impacts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

Part 1 (30 points).

1.1	Using the JHelioviewer software find the CME which occurred on May 28, 2021, by selecting 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. Indicate, in a table, the date and time of each image that you have used.	10.0pt

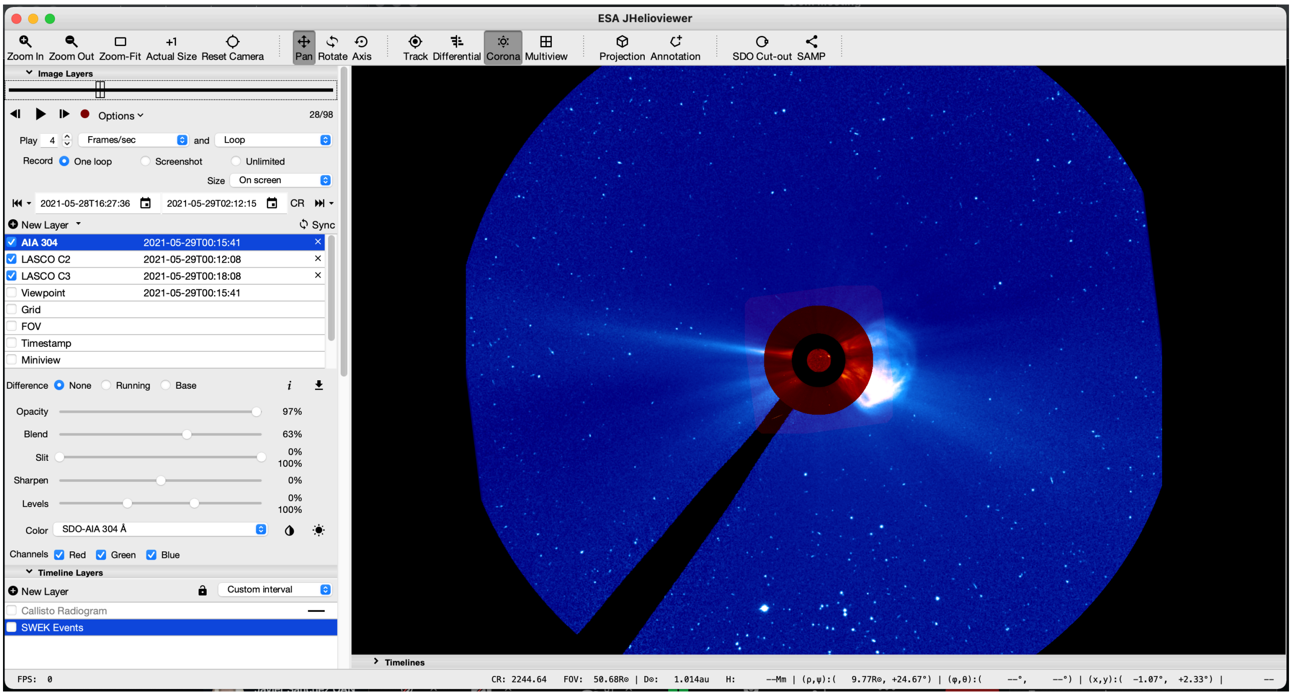

Figure 2: Exploration of solar data for May 28, 2021 with JHelioviewer.

1.2	Use a selection of images to measure the distance of the CME front from the Sun in km.	10.0pt

1.3	Extend the table of data (that you constructed in previous part) to include • Date and time (as reported in 1.1) • Distance of CME front from the Sun in km (as reported in 1.2) • Cumulative velocity in km/s (e.g. if you are at the 4th image, the mean velocity between onset of CME until the time of the 4th image), • Velocity per time interval in km/s (e.g if you are at the 4th image, the mean velocity of CME between the times of the 3rd and 4th image). Make this table in the working sheet.	10.0pt

Note: Both the velocities are to be calculated with respect to the Sun.

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

Part 2 (15 points).

2.1	Make distance-time and velocity-time graphs (for both cumulative and velocity per time interval) using the measured and calculated data from your table.	15.0pt

Part 3 (10 points).

3.1	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.	10.0pt

Part 4 (10 points).

From the following statements, mark which are TRUE and which are FALSE.

4.1	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.	2.0pt
4.2	A more accurate analysis and measurements of the CME evolution should consider the differential rotation of the Sun, and therefore the calculated velocities will be affected.	2.0pt
4.3	Any software (numerical) misalignment among the images when creating the mosaic will have direct effects on the precision of the calculations.	2.0pt
4.4	The different assumptions made in order to construct the model displayed in a heliospheric density map in Figure 1, may affect the estimation of the Sun-ParkerSP distance.	2.0pt
4.5	The interaction of the CME-front with the remnant dust left by the 2019 Borisov comet broadens and diffuses the images. This reduces the contrast in the images, substantially increasing the uncertainty in determining the CME-front and its propagation.	2.0pt

Part 5 (10 points)

5.1	The CME front carries a large number of protons and alpha particles. Calculate the energy (in eV) of a single proton and a single alpha particle as measured by the Solar Wind Electrons Alphas and Protons (SWEAP) instrument on board the ParkerSP. Consider only the mechanical energy of the particles resulting from the propagation of the CME front, neglecting all other forms of energy.	10.0pt

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, 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”).

Group Radio Astronomy (115 points)

Please read the general instructions in the separate envelope before you start this problem.

Measuring the Perseus arm using 21 cm HI line data

Context

Our goal here is to kinematically estimate the distance of (part of) the Perseus Arm of the Milky Way (Figure 1), from the center of the Milky Way, based on the line-of-sight velocity of neutral hydrogen gas via its 21 cm emission line.

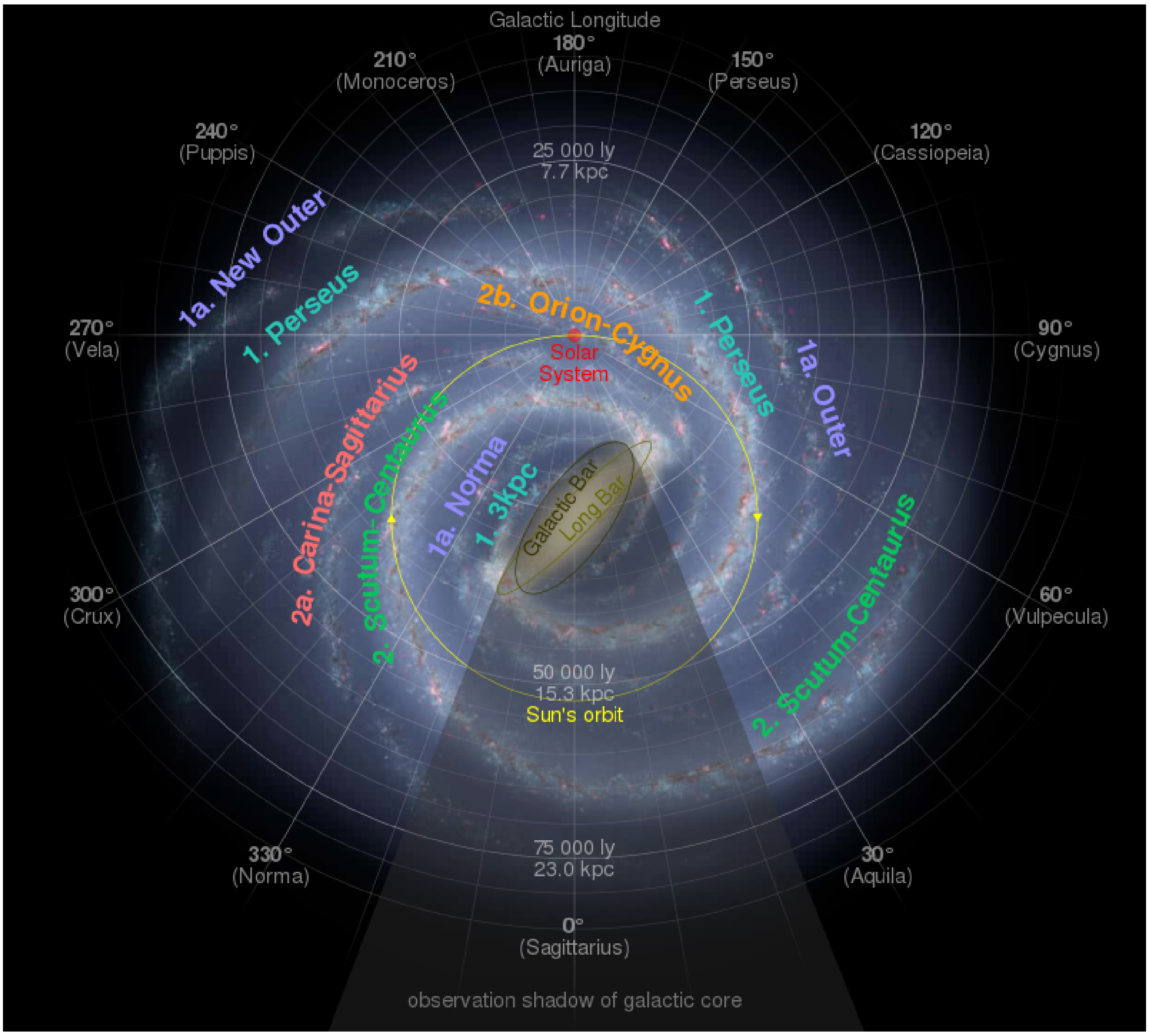

Figure 1: Distance-galactic longitude map of the Milky Way arms https://en.wikipedia.org/wiki/Perseus_Arm#/media/File:Milky_Way_Arms_ssc2008-10.svg

For this problem we will use a subset of the Canadian Galactic Plane Survey (CGPS, Figure 2), in which individual radio telescope pointings can each yield the 21 cm line spectrum emitted by all the galactic neutral hydrogen along the line of sight of the radio telescope.

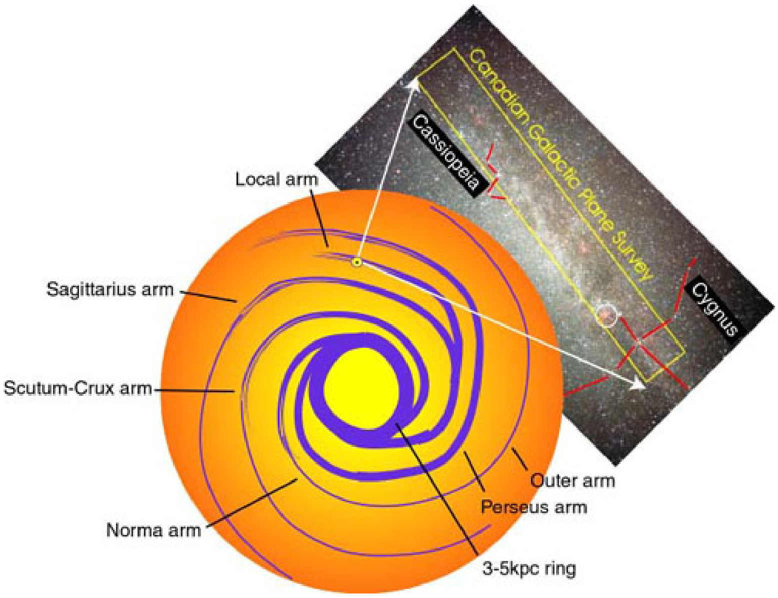

Figure 2: Canadian galactic plane survey http://www.ras.ucalgary.ca/CGPS

By translating the Doppler wavelength shift of the 21 cm emission to a line-of-sight velocity, it is then possible to identify individual emission components that correspond to distinct galactic arms. This identification allows for a reconstruction of the shape of each arm with respect to the Galactic Center.

In the spectrum corresponding to a radio telescope pointing, the Perseus arm can be readily identified because it is often the brightest feature along each line of sight.

The frame of reference of the radio telescope observations can be taken to be the Sun, located at a distance R_0 from the Galactic Center (GC). The telescope has a pointing along a Line of Sight (LOS) defined by a galactic longitude l and a fixed galactic latitude $b = 0$. Along this LOS, the telescope picks up the emission of a parcel of neutral H gas from the Perseus arm that is located at a distance r from the Sun. This same parcel of gas is located at a distance R from the Galactic Center. Let us assume that both the Sun and the gas parcel are in exact circular orbits around the GC. Additionally, it can be assumed that both the Sun and the gas parcel are in the region where the rotation curve of the Milky Way is flat. The measured (Doppler) velocity is denoted as $v_{\rm LOS}$, which equals to the velocity of the gas parcel along the line of sight.

Data set

For this problem we attach a .csv file (21cmsurvey_full.csv, Excel and other spreadsheet software-readable) which contain 21 cm HI line brightness temperature (T_b) data vs. line-of-sight velocity (V_{LOS}) for a range of galactic longitudes (for galactic latitude $= 0$).

Row **1**: Line-of-sight velocities v_{LOS} (173 values, units: kms^{-1}).

Column **1** (after row 1): Galactic Longitude l (1024 values, units: $^{\circ}$).

Rows **2-1025**: 21 cm HI Brightness Temperature T_b (units: K). Each row yields the spectrum for the pointing defined by l (row name - column 1). There are thus 1024 spectra. Each spectrum has 173 T_b measurements, one for each v_{LOS}.

	A	B	C	D	E	F	G
1	longitude	17.499242	16.674782	15.850322	15.025862	14.201402	13.376942
2	142.195	7.6806355	-3.6773872	10.236036	12.072731	2.6496887	-5.4096527
3	142.2	-2.3566856	-17.443382	10.948601	15.752264	-5.6430779	-4.0766678
4	142.205	-7.2586327	-16.816818	11.409309	14.382421	-8.1247673	-2.1908302
5	142.21	-4.8997993	-1.3861237	8.1782017	0.1741447	-6.5460701	2.8831139
6	142.215	1.4211311	17.361675	3.865963	-19.79607	-5.4956512	10.672174
7	142.22	10.801174	29.229548	6.5995045	-28.279266	-6.2942162	17.140533
8	142.225	15.174841	25.408731	12.852865	-18.843937	-8.4810486	11.249598
9	142.23	11.863876	11.36631	13.676001	-3.8985252	-8.6407623	-3.4193878
10	142.235	1.5808449	-5.765934	4.6522408	3.5158234	-6.70578	-18.493797
11	142.24	-3.855526	-13.573421	-5.8457909	0.7269974	-4.1995239	-23.408031
12	142.245	-1.1465569	-7.5473442	-7.0313492	-3.400959	-1.7116928	-18.352516
13	142.25	5.9913673	8.6634827	2.0968399	-1.6011238	4.3635292	-6.9637794
14	142.255	9.1303349	24.567169	13.166147	4.2713852	13.448717	4.9778061

Part 1 (50 points).

1.1	Make a spectral plot of v_{LOS} vs. T_b for an adequate number of different values (at least 20 plots) of galactic longitudes covering the full range of observations. Identify the peak line of sight velocity of the Perseus gas parcel at each of the plotted longitudes. Make sure to evenly sample the data set. **Note:** Use the plot of the first or the last longitude as a guide to identify correct peaks in the plots at the intermediate longitudes.	45.0pt

1.2	Why does the emission near $v_{LOS} = 0$ (which we associate with our local arm) have a lower brightness temperature than the emission from the Perseus arm?	5.0pt

Part 2 (20 points).

2.1	Derive an expression to calculate R from v_{LOS}, $v_{\odot}$, and l. You can assume: • That both the Solar System and and the Perseus arm gas parcel along the line of sight have a purely tangential velocity, with a negligible radial component. • A flat galactic rotation curve, i.e. $$\lvert\mathrm{v}\rvert = \lvert\mathrm{v}_{\odot}\rvert$$ where v is the velocity of the gas parcel.	20.0pt

Part 3 (20 points).

3.1	Using the v_{LOS} values you found earlier, make a plot of galactic longitude l vs. R (radius with respect to the Galactic Center, in kpc) for the Perseus arm. Find the average distance of the Perseus arm for the given longitude range. Also report the standard deviation in your result. Use the values: $$v_{\odot} \approx 225\ kms^{-1}$$ $$R_0 \approx 8\ \mathrm{kpc}$$	20.0pt

Part 4 (25 points).

4.1	The data also shows 21cm emission from the Norma arm of the Milky Way, which is its outer arm. This emission is most clearly seen around the galactic longitude of 145^o. Repeat the exercise for the Norma arm to find its distance from GC. Use at least 5 data points to determine the distance of the Norma arm from the Galactic Centre (at these galactic longitudes).	25.0pt

Simulated Sky (75 points) - 17 questions in 45 minutes.

Please read the general instructions before you start this problem.

On the projection screen in front of you, a series of images will be projected. Look at the image and answer the following questions:

Image 1 (2 minutes).

1.1 (6.0 pt)
Identify the drawn lines on the image.

Line Number:	1	2	3
Celestial Equator			
Ecliptic			
Local Meridian			
Local Vertical			
Zero RA			
Galactic Equator			

Image 2 (2 minutes).

1.2 (3.0 pt)
This image was taken from the town of Fada in Chad. What is the latitude of this place? Select only one choice:

A. 10°

B. 17°

C. 22°

D. 33°

Image 3 (3 minutes).

1.3 (4.0 pt)
Two of the following stars are transiting the meridian in the image. Tick the boxes to those stars.

Arcturus	Mizar	Spica	Regulus

No Image for questions 4, 5 and 6 (8 minutes)

1.4 (2.0 pt)
If the age of the Moon is 27.5 days, in which direction can we observe it and at what time?. Select only one choice.

A. Before sunrise to the east.

B. After sunset to the west.

C. Close to zenith at sunrise.

D. At 9 am rising in the East.

1.5 (5.0 pt)
Which of the Right Ascensions (RA) listed below will approximately coincide with the local meridian at Pune, India $(74°E)$on April 10 at $19:15$ local time?
A. 6 h

B. 7 h

C. 8 h

D. 9 h

E. 10 h

1.6 (4.0 pt)
At what time during this night (April 10) would we find the Regulus $[\alpha\; Leo\; (RA\; 10h\; 08m\; 22.3s,\; Dec\; = +11°58'02")]$ at its maximum altitude as seen from Pune, India? Select only one choice.

A. 18:00h

B. 19:00h

C. 20:00h

D. 21:00h

E. 22:00h

Image 4 for questions 7, 8, 9 and 10

The projected sky now corresponds to -30 **of latitude** (South) with -74 **longitude** (West).

Image 4 (2 minutes).

1.7 (3.0 pt)
Select the constellations pack that crosses the celestial equator on the image.

A. Ori, Tau, Cet, Eri, Psc, Aqr, Aql, Ser

B. Mic, Tau, Per, Cae, Mon, Aql, And, Ser

C. Gru, Tau, Cha, Ara, Aqr, Aql, And, Aps

D. For, Tri, Cet, Psc, Sct, Aql, And, Ser

Image 4 (2 minutes).

1.8 (6.0 pt)
Choose the name of stars indicated by the arrows (tick in the correct cell).

Star Number	1	2	3
Achernar			
Alnair			
Altair			
Alnath			
Ankaa			
Canopus			

Image 4 (3 minutes).

1.9 (6.0 pt)
Are the following Messier objects presented in the projected sky?. Select (X) YES or NO depending on the case.

Object	YES	NO
M15 (Peg)		
M16 (Aql)		
M27 (Vul)		
M6 (Sco)		
M15 (Cas)		
M27 (CMi)		

Image 4 (3 minutes).

Choose the name of the selected stars (tick in the correct cell). If the same object is listed more than once, choose only the option with the correct constellation:

1.10 (3.0 pt)

Star Number:	1	2	3
Miaplacidus (Car)			
Miaplacidus (Lac)			
Sham (Sge)			
Sham (For)			
The Persian (Gru)			
The Persian (Ind)			

Image 5 for questions 11 and 12 (4 minutes).

1.11 (4.0 pt)
From the list below select the option that contain the constellations that are along the line of the ecilptic:

A. Psc, Cap, Sgr, Oph

B. Lib, Sco, Oph, Sgr

C. Cap, Sge, Lib, Vir

D. Sgr, Oph, Sco, Vir

E. CrA, Sco, Oph, Leo

1.12 (3.0 pt)
Which constellation or part of contellation is encircled in the image?

A. Sagittarius (Sgr)

B. Corvus (Crv)

C. Telescopium (Tel)

D. Corona Australis (CrA)

Image 6 (2 minutes).

1.13 (3.0 pt)
You are making an observation through a telescope pointed towards the centre of the galaxy. You find an interesting object as shown in the image 6. What is this object?

A. M42 - Orion Nebula

B. M31 - Andromeda Galaxy

C. NGC 2024 - Flame Nebula

D. M8 - Lagoon Nebula

E. M20 - Trifid Nebula

Image 7 (2 minutes).

1.14 (5.0 pt)
In the Messier Astronomical Catalogue there's a mysterious object: a galaxy. This object in the image cannot be easily identified. Some astronomers had said that it was a duplicate of another Messier Object, but here We have it as an original and awesome galaxy. Wich object is this?

A. M31 - Andromeda Galaxy

B. M33 - Triangulum Galaxy

C. M51 - Whirlpool Galaxy

D. M101 - Pinwheel Galaxy

E. M102 - Spindle Galaxy

Image 8 (2 minutes).

1.15 (2.0 pt)
Estimate the magnitude of Shaula in the constellation Scorpio.

A. 1

B. 1.5

C. 2

D. 2.5

C. 3

Image 9 (4 minutes).

1.16 (8.0 pt)
Several stars have been indicated in image 9. Tick the stars indicated in the table below.

Star Number:	1	2	3	4
Acubens				
Adhara				
Aludra				
Alzirr				
Arneb				
Gomeisa				
α Mon				
Mebsuta				
Mirzam				
Wasat				

Image 10 (4 minutes).

1.17 (8.0 pt)
A Messier object has been indicated in image 10. Tick the correct cell below to indicate what it is.

Object Number:	1	2	3	4
M 41				
M 42				
M 46				
M 45				
M 48				
M 50				
M 64				
M 93				