Cume #436

75 Points Possible; 55 Points is Guaranteed Pass
passes below this score are a distinct possibility
Administered October 5, 2019

MusE GAs FLOw and Wind (MEGAFLOW) IV: Tomography of a galactic outflow

Zable, Bouché, Schrortter et al. 2019, MNRAS, submitted preprint (10 pages)

You may use a calculator, but no programmed formulae. Some physical constants are supplied in the exam as needed. Please start each question (by number) on a new sheet of paper, write on only one side of the paper, and staple them together in order of question number when finished. Please present your results in the order that the individual questions appear and clearly label each problem number. **Do not write in the upper left corner of your paper - do not obscure your work or the problem number underneath the staple!**.

1. **[12 pts]** Write a very brief overview of this paper. Clearly separate your responses into the following well-defined categories– I am testing that you can parse and then articulate the author's (a) motivations, (b) observations, (c) analysis, and (d) results.

   (a) [3 pts] Motivation: In two sentences maximum, describe the big picture broader astronomical context motivating this work.

   ANSWER: The CGM is an important component for understanding galaxies and how they evolve as it traces the baryon cycle between the ISM and the IGM. Results over the last decade have demonstrated that there is a bipolar outflow from galaxies, but gas kinematics and geometry need to be tested together to support this finding, and that is the aim of this paper using a simple outflow cone model constrained by absorption from two lines of sight.

   (b) [3 pts] Data: In two sentences maximum, describe the data employed and the observations.

   ANSWER: The authors employ MUSE data that provides both spectral and spatial imaging information of a target galaxy and the objects captured in the field of view of instrument. They also employ a high resolution, high-signal to-noise UVES/VLT spectrum of a QSO that is background to the target galaxy.

   (c) [3 pts] Analysis: In two sentences maximum, describe scientific analysis performed (do not describe results or findings here).

   ANSWER: The authors measure the observed orientation of the target galaxy and the kinematics of absorption lines from two different lines of sight through the CGM of the target galaxy and compare them the predicted absorption lines from their simple outflow cone model. They explore wind speeds, opening angles, and orientations of the cone model.

   (d) [3 pts] Results: In two sentences maximum, describe the *new* most important conclusion(s) [those central to the larger picture addressed by the paper, i.e., your "walk away" results].

   ANSWER: The authors claim that their model fits the some of the absorbing data but also fails to fit some of the absorbing data. They claim that they have shown the gas is consistent with a cone outflow model if the absorption takes place on the surface (or skin) of the cone, but that an additional gas component, such as a high velocity clouds not associated with the outflow wind, must be present as well.

2. **[16 pts]** Galaxies. Answers are being sought at the nearest one decimal place order of magnitude accuracy, i.e., the mass of the sun 2×10^{30} kg.

   (a) [4 pts] What is the virial radius of a galaxy, i.e., how is the virial radius of a galaxy defined in the cosmological context (words and/or equations will suffice, but if you write an equation, you must explain the terms)? If the mass the total mass of a galaxy does not change from redshift 3 to redshift 0, how will its virial radius evolve?

   ANSWER: The virial radius, R_v, is defined as the radius of a sphere surrounding a cosmic overdensity (dominated by a dark matter halo) such that the average density inside the sphere is Δ_c times the critical density $\rho_c(z)$. To a good approximation, $\Delta_c = 18\pi^2$, thought there is a redshift dependence. Sometimes, authors assume $\Delta_c = 200$ and write R_{200}. Though it is not required to write the equation, I provide it here.

$$\bar{\rho}(r \leq R_v, z) = \Delta_c \rho_c(z) = \Delta_c \frac{3H^2(z)}{8\pi G} \, ,$$

where $H(z) = H_0 E(z)$, and $E^2(z) = (1+z)^3 \Omega_m + \Omega_\Lambda$. It turns out that Δ_c has a weak redshift dependence as well, but I won't write that out, and we can assume that it is a constant for our discussion. The predominant redshift dependence of R_v occurs because the critical density of the universe is decreasing with time. For a fixed mass, if the virial radius did not evolve with redshift, then the average density in the sphere would rise above the factor $\Delta_c \rho_c$. The virial radius must be increased in order to encompass additional lower density within the volume in order to maintain a ratio of $\bar{\rho}(r \leq R_v, z)/\rho_c(z) = \Delta_c$.

(b) [6 pts] What is the approximate *total* mass of the Milky Way galaxy contained in its virial radius? What is the approximate value of the virial radius of the Milky Way galaxy (you can simply state it if you know the answer)? Approximately, what fraction of the virial radius does the visible disk of the Galactic extend out to?

ANSWER: The total mass is roughly 1–2 $\times 10^{12}$ $M_\odot$. The virial radius is approximately 200 kpc. The visible disk is about 100,000 lys or roughly 30 kpc, or about $\simeq 30/200$ or $\simeq 15\%$ of the virial radius (depending on the value used for the virial radius).

(c) [6 pts] To help us understand galaxies, we break them down into several physically motivated components and each of these components comprises a certain fraction of the total mass of the galaxy system. For a Milky Way-like galaxy, list these components and provide a rough estimate of the percentage of mass contained in that component.

ANSWER: The mass components are (1) dark matter, (2) stars, and (3) baryonic gas. The fraction in each changes as a function of galactocentric distance (radial distance from the center of the galaxy). Inside the virial radius, the stars comprise roughly 4% of the total mass. The gas mass, including all phases and both the ISM and CGM is on the order of the stellar mass, about 12%. The dark matter makes up roughly 84%. These are rough numbers that apply for the Milky Way. For lower mass and higher mass galaxies, they have a higher percentage of dark matter!

3. **[10 pts]** In the Introduction, in the beginning of the Discussion, and then summarized in the Conclusion, the authors offer a description of the modern view of the CGM as probed using Mg II absorption.

(a) [5 pts] In your own words, describe the spatial distribution of the CGM gas traced by Mg II ions. Also describe the kinematic or velocity distribution of this phase of the CGM gas.

ANSWER: The CGM is a gaseous region surrounding a galaxy that serves as the interface between the ISM and the IGM. Gas flows through this region and its spatial and kinematic distribution provide insight into the baryon cycle- the cycle of normal baryonic gas in, out, and through galaxies. Mg II traces metal enriched gas that has (in astrophysical terms) a moderate low density ($n_{\rm H} \simeq 10^{-2}$ cm^{-3}) and warm temperature ($T \simeq 10^{4.5}$ K). This phase of gas is observed to be spatially and kinematically distributed in two dominant zones (1) in a bi-polar cone of gas outflowing from the galaxy central region and perpendicular to its disk. It is believed that this is a superwind that is common to most star forming galaxies. (2) in a planer disk-like extension to the galaxy disk that is coupled to the rotation of the galaxy disk. It is believed that this material is slowly accreting into the outer regions of the galaxy disk and will eventually mix into the ISM.

(b) [5 pts] To compliment your description, draw a diagram. (i) Start with the stellar component of a spiral galaxy viewed edge on. (ii) Draw a circle that represents the approximate location of the virial radius. (iii) Draw the spatial location of the gas traced by the Mg II ion. (iv) Draw some arrows that illustrate the general characteristic of the velocity field of the gas.

ANSWER: See attached figure.

4. **[18 pts]** Some atomic physics, spectroscopy, and photons. You may benefit from knowing the value of these constants: $h = 4.135667696 \times 10^{-15}$ eV s and $c = 299,792,458$ m s^{-1}, and the conversion factor 1 Å $= 10^{-10}$ m.

(a) [6 pts] The Mg II $\lambda\lambda 2796, 2803$ doublet is due to a fine structure splitting in the first excited state of the singly ionized magnesium atom. The precise central wavelengths of the absorbed photons are 2796.352 Å and 2803.531 Å. The ground level for the doublet transitions is the 3s state ($^2\mathrm{S}_{1/2}$) and the upper level is a split 3p state ($^2\mathrm{P}_{1/2}$ and ($^2\mathrm{P}_{3/2}$). What is the magnitude of the energy splitting (in eV) of the split upper 3p state?

ANSWER: As the photons share the same lower energy level, the energy splitting of the 3p state is the energy difference of the two photons of the doublet. The energy of a photon is $E = hc/\lambda$. From the constants given, we have $hc = 1.2398 \times 10^{-6}$ eV m (though you have nine significant digits for this quantity, we will not use them all). Converting this into our wavelength units, we have $hc = 12,398$ eV Å. Our energy differences is then

$$\Delta E = E_2 - E_1 = hc \left(\frac{1}{\lambda_1} - \frac{1}{\lambda_2} \right) = 12,398 \cdot (0.000357608 - 0.000356669) \quad \mathrm{eV} \,,$$

and we obtain 0.0113 eV. A diagram is presented for additional clarification of the energy structure of this fine structure doublet.

(b) [6 pts] Let's say you are studying just the Mg II $\lambda 2796$ line in absorption from gas clouds at cosmic distances. You want to be able to resolve multiple cloud components that are separated by no more than 3 km s^{-1} for a gas complex that is at redshift $z = 0.5$. If the resolution of the spectrograph is defined as $R = \lambda/\Delta\lambda$, where λ is the wavelength of the observation and $\Delta\lambda$ is the FWHM of an unresolved absorption line, what is the minimum resolution spectrograph you would need? Explain the reasoning or any assumptions you applied to obtain your answer.

ANSWER: I will assume that $c = 300,000$ km s^{-1} for this. Using $\Delta\lambda/\lambda = \Delta v/c$, we can rewrite $R = \lambda/\Delta\lambda = c/\Delta v$. For $\Delta v = 3$ km s^{-1}, we obtain $R = 100,000$. Note that, since the the velocity splitting is defined in the rest-frame of the absorber, we can directly apply $\Delta\lambda/\lambda = \Delta v/c$ and we find that the answer can be expressed independent of observed wavelength! If we do this the long way, we first must obtain the observed wavelength, which is $2796 \cdot (1 + z) = 4194$ Å for $z = 0.5$. We then must determine $\Delta\lambda$, which is $\lambda(\Delta v/c) = 4194 \cdot (3/300,000) = 4.194 \times 10^{-2}$ Å. We then get $R = (4.194 \times 10^3)/(4.194 \times 10^{-2}) = 100,000$.

(c) [6 pts] Ground-state neutral hydrogen is ionized by photons such that $h\nu_0 > 13.598$ eV. Let's say that you have a gas cloud that is subjected to a radiation field that is described by a mean intensity given by J_ν [erg s^{-1} cm^{-2} Hz^{-1} str^{-1}]. Write the expression that gives n_γ, the number density [photons cm^{-3}] of all hydrogen ionizing photons. [HINT: unit analysis can be very helpful].

ANSWER: We will want to obtain an expression for the photon number density per unit frequency per unit solid angle and then integrate over all photon frequencies greater than ν_0 and over all solid angles, thus yielding the number density of hydrogen ionizing photons. We start with the mean intensity, J_ν [erg s^{-1} cm^{-2} Hz^{-1} str^{-1}], which is the energy per unit area per second per unit frequency per unit solid angle. This is an "energy flux" per unit solid angle per unit frequency. We first want to convert this energy flux into a number flux, which we accomplish by dividing by the energy, $J_\nu/h\nu$. We now have number flux per unit solid angle per unit frequency [photons cm^{-2} s^{-1} Hz^{-1} str^{-1}]. The convert this number flux to a number density we divide by the velocity of the particles (passing through the unit area each second), which are photons in this case and thus $v = c$. Thus, step yields, $J_\nu/ch\nu$, which is the number density of photons per unit frequency per unit solid angle [photons cm^{-3} Hz^{-1} str^{-1}]. We now integrate over all solid angle to obtain the number density per unit frequency [photons cm^{-3} Hz^{-1}]. Assuming an isotropic mean intensity, we obtain $4\pi J_\nu/ch\nu$. To get the number density of all hydrogen ionizing photons we now integrate over all frequencies greater than ν_0,

$$n_\gamma = \frac{4\pi}{c} \int_{\nu_0}^{\infty} \frac{J_\nu}{h\nu} \, d\nu \quad \mathrm{cm}^{-3} \,.$$

5. **[8 pts]** Consider the toy model that the authors use to help them claim the first"tomography" of the CGM. In Figure 3, the authors show three absorption components, A, B, and C in the QSO sightline.

(a) [4 pts] What is the interpretation of components A+B? What is their (model dependent) interpretation of why these two components can be separated in velocity in the spectrum?

ANSWER: The interpret these two components as outgoing wind on opposite sides of the surface, or skin, of the outflow cone. The only way the two components could be observed as separated in velocity (and not a single broad component) is if the absorbing gas is confined to the skin of the cone of the outflowing wind. In their model, they must assume the absorbing gas is on the skin of the cone or they cannot produce the two separate components.

(b) [4 pts] What adjustment to their first model obtained for the "back1" line of sight do the authors explore in order to fit component A in the QSO sightline? What is their physical interpretation if the adjustment is to be adopted as physically meaningful?

ANSWER: In order to get component A in their model at the observed velocity of component A in QSO spectrum, the authors must reduce their v_{out} from their favored 150 km s^{-1} to 75 km s^{-1}. Of course that would mess up the location of component B in their model. So, they interpret this slower velocity as a deceleration in the outflowing gas (for this component).

6. **[11 pts]** Component C in the QSO line of sight fails the model. What if, as the authors suggest, component C is some high velocity material in the halo that is not associated with the outflow wind. Assume it is a radially *inflowing* cloud with radial velocity v_r and a measured line of sight velocity of $v_{los} = +100$ km s^{-1} (as seen in Figure 3).

   (a) [3 pts] What side of the plane of the sky would this cloud need to be on? The observer's side (negative $z_{\rm sky}$)? Or the QSO side (positive $z_{\rm sky}$)? Looking at the Figure 1(c) may be helpful for visualization. Provide a drawing that illustrates your answer.

   ANSWER: See the included diagram. Positive line of sight velocity is defined as moving away from the observer. If the cloud is infalling into the galaxy along a radial vector to the galactic center, the cloud would need to be on the observer's side of the plane of the sky (negative $z_{\rm sky}$).

   (b) [4 pts] Show that for a cloud at location $z_{\rm sky}$ along the line of sight, the radial velocity, v_r, can be written $v_r = v_{los}\sqrt{1+(D/z_{\rm sky})^2}$, where D is the line of sight impact parameter.

   ANSWER: We define D as the impact parameter and R_g as the galactoccentric distance. From the included diagram, we have $\cos\theta = z_{\rm sky}/R_g$, where $R_g = \sqrt{D^2+z_{\rm sky}^2} = z_{\rm sky}\sqrt{1+(D/z_{\rm sky})^2}$. From similar triangles, we have $\cos\theta = v_{los}/v_r = z_{\rm sky}/R_g$, or $v_r = v_{los}(R_g/z_{\rm sky}) = v_{los}\sqrt{1+(D/z_{\rm sky})^2}$.

   (c) [4 pts] At what $|z_{\rm sky}|$ is the cloud at when $|v_r|$ is equivalent the wind speed, v_{out}, of the author's favored outflow model? What is the galactocentric distance of this cloud if it resides at this $|z_{\rm sky}|$?

   ANSWER: The wind speed that the author's favor is $v_{out} = 150$ km s^{-1}. We have $v_{los} = +100$ km s^{-1} and $D = 17$ kpc, a little algebra yields

$$|z_{\rm sky}| = D\left[\left(\frac{v_r}{v_{los}}\right)^2 - 1\right]^{1/2},$$

   and a straight forward calculation yields $|z_{\rm sky}| = 19$ kpc. From $R_g^2 = D^2 + z_{\rm sky}^2$, we obtain $R_g = 25.5$ kpc.

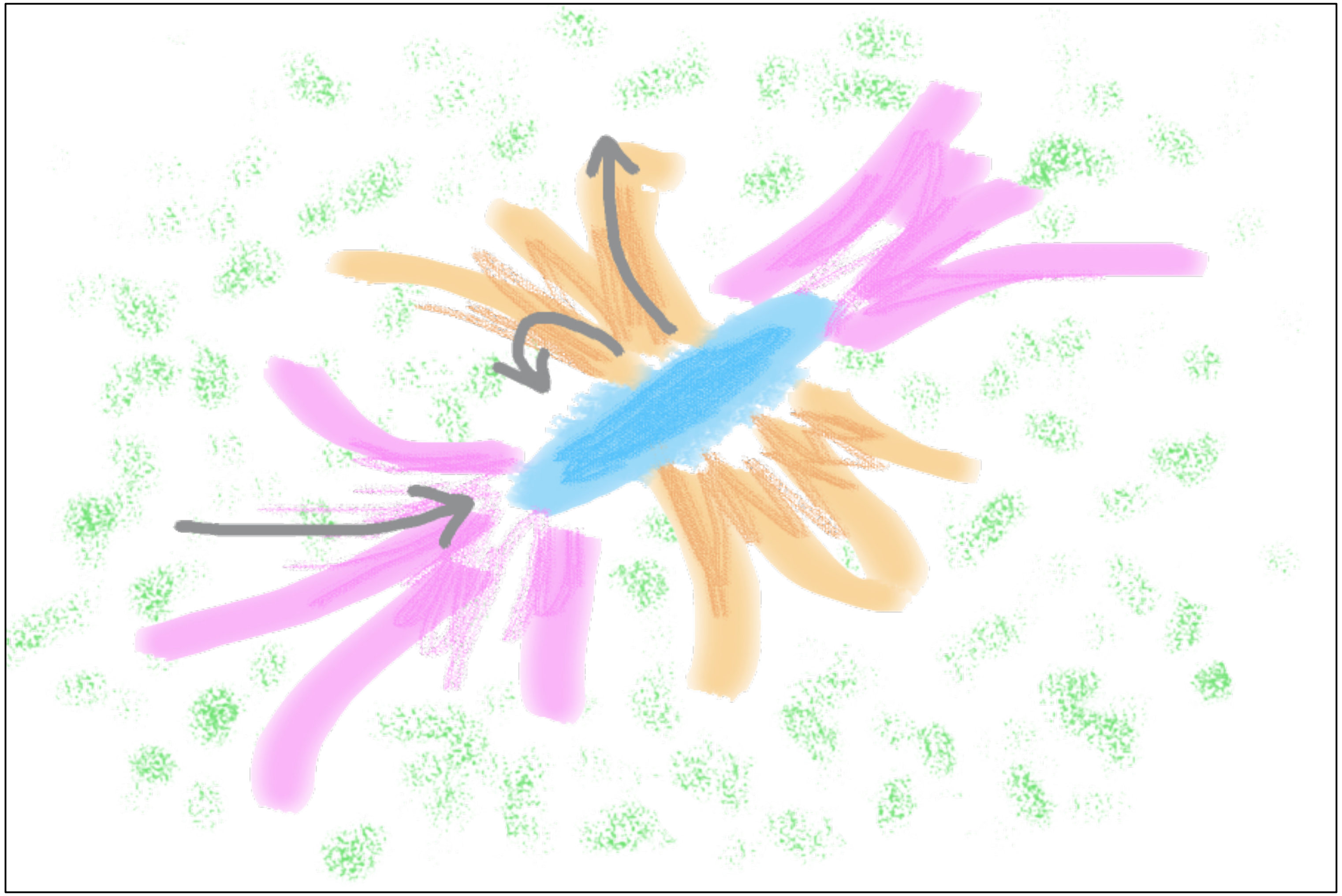
Figure for Problem 3

Grey arrows represent velocity flow

Pink is planer inflow

Yellow is bipolar outflow

Blue is stellar disk



Credit: Christopher Wotta

Figure for Problem 4

The MgII fine structure

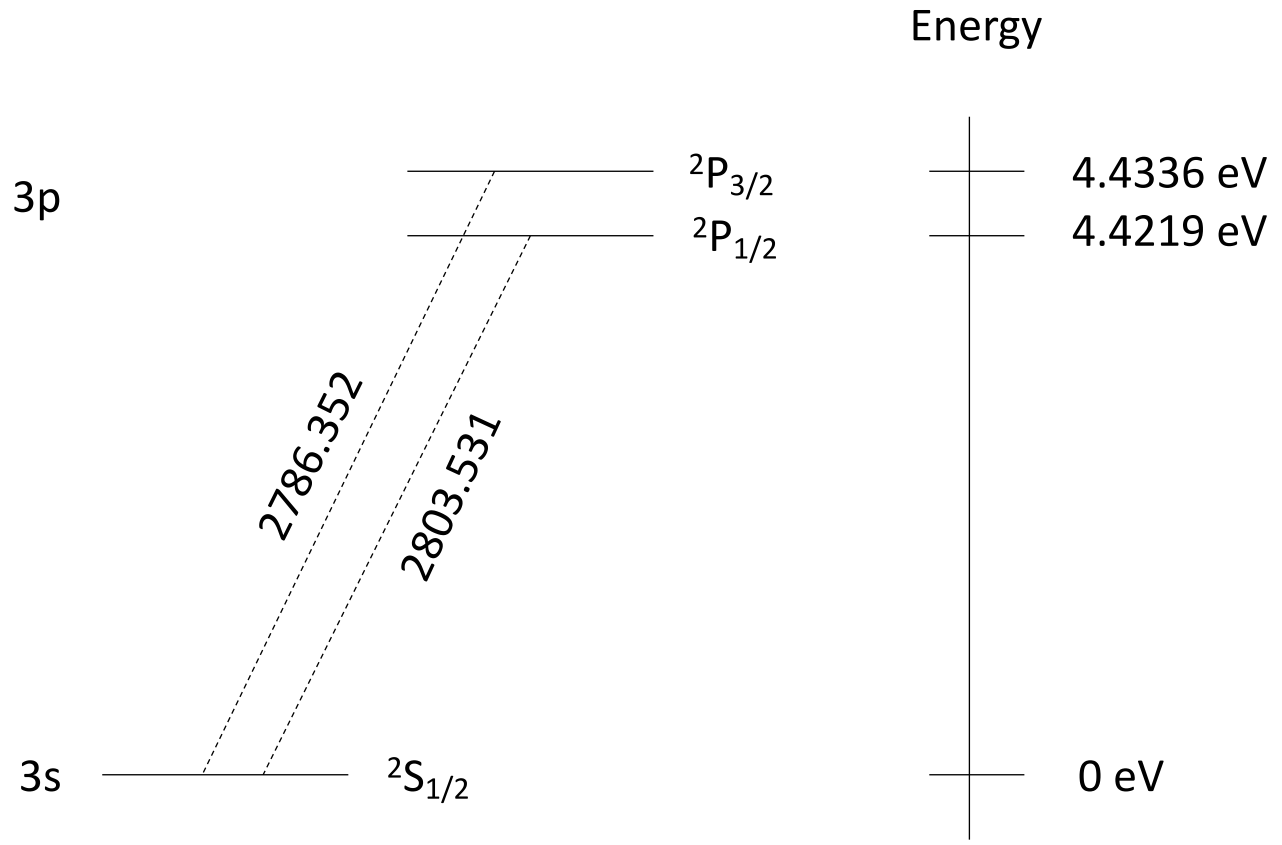
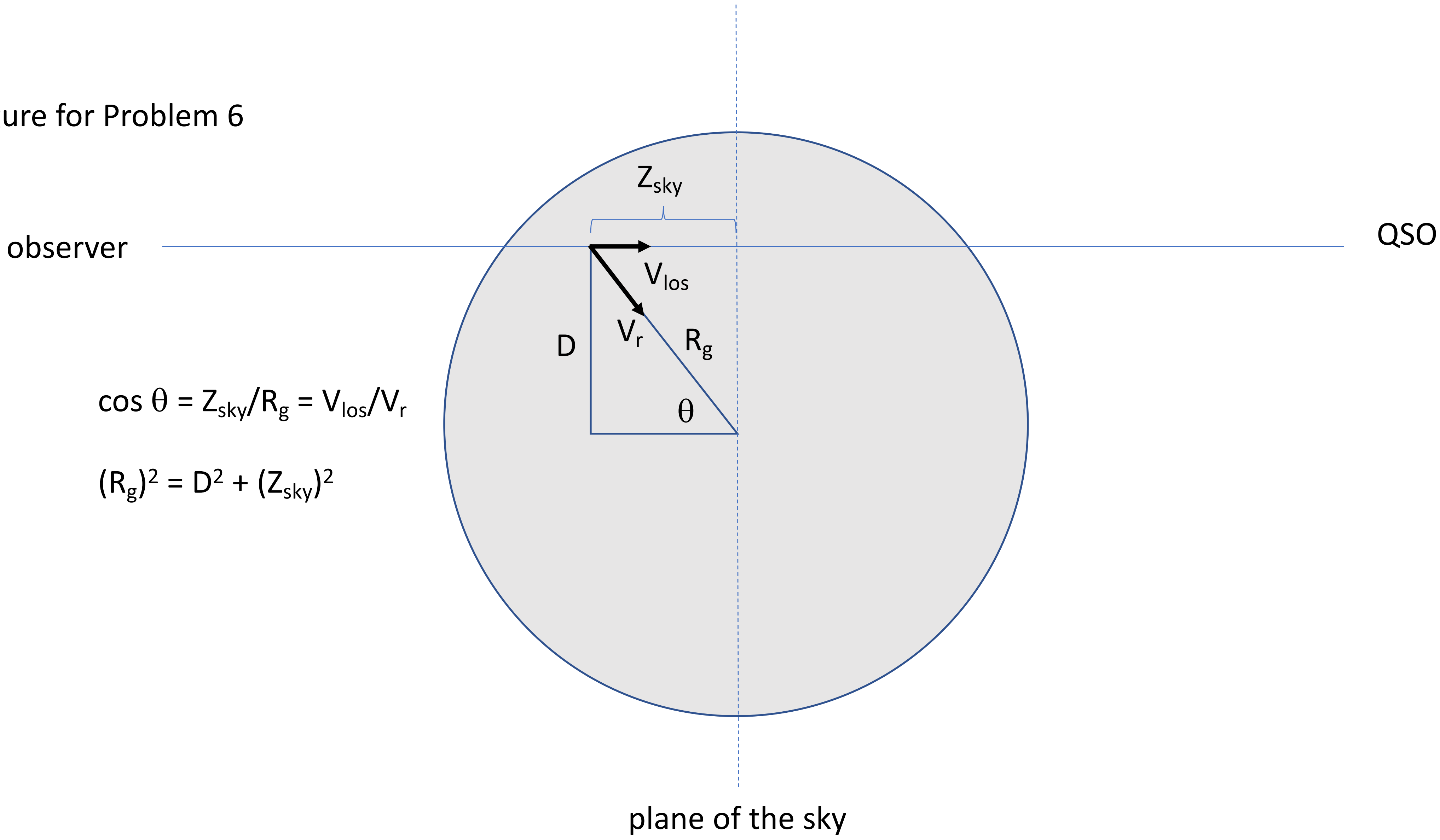


Figure for Problem 6



$\cos\theta = Z_{sky}/R_g = V_{los}/V_r$

$(R_g)^2 = D^2 + (Z_{sky})^2$