Cume exam ..., given by R. Walterbos #330

Please read all the questions carefully. If anything is not clear to you and leads to confusion as to how you interpret that question, then comment on that in your answer.

This cume is in part based on the paper "The Detection of Molecular Gas in the Outskirts of NGC 6946" by Braine etal., 2007, ApJ 669, L73. Note that not all questions are related to the paper, although several of them do make use of the information in the paper. I tried to phrase the question such that even without having taken ISM or Radio, you might be able to get a long way to the answers.

Each question is 5 pts, maximum number of points is 50. Scores over 75% are a definite pass.

1. What is meant with the quantity "R_{25}" that is used throughout in the paper?

2a. Why do they observe CO to trace molecular hydrogen gas? In particular, why not observe the H_2 molecule itself? How is the CO molecule excited such that it will emit the lines observed in this paper?

2b. Molecules can generally have three principal types of transitions that give rise to emission of photons. One of them is vibrational transitions. What are the other two types? What type of transitions are observed in this paper?

3a. Calculate the beam sizes of the IRAM telescope at the two frequencies that were observed and see if you agree with the values given in the paper. In general there can be slight differences from the "theoretical beam size". What can cause such differences for a radio telescope?

3b. Why would they use a "position switching mode" for the observations (page L74)?

3c. Verify the spatial scale for the distance to NGC 6946 given in the paper (the conversion from angular to linear size).

3d. For a radio telescope beam size as given in the paper for the CO 1-0 transition, convert a "beam-averaged column density" of 0.5×10^{20} H_2 molecules per cm^2 to a total mass in molecular gas detected inside one beam for the distance quoted (5.5 Mpc).

4a. The systemic radial velocity (helio-centric) of NGC 6946 is 46 km/s. For the orientation as shown in Figure 1 and given the spectra in Figure 2, in which direction is the galaxy rotating, clock-wise or counter-clock wise? Explain your answer.

4b. Assume that NGC6946 is a disk galaxy with a flat rotation curve and circular orbits for the gas clouds. Which group of points will have the most different observed radial velocities compared to the systemic velocity of NGC6946, those near P2 or those near P8? Explain why.

4c. Under the assumptions of a flat rotation curve with gas on circular orbits in a disk, calculate a minimum for the mass of NGC 6946 interior to point P8, assuming a spherical mass distribution. You can find the relevant data values that you need from Table 1, Figure 1, and Figure 2. Hint: Picture a particle in circular motion, as seen perpendicular to your line of sight. Place a point A on the circle. Now incline the circle around a line going through the center that does not intersect point A. You need to convert the observed radial velocity at point A to an actual circular velocity. You will need to use some geometry, and find the inclination of the plane of NGC 6946 to the sky plane and the position angle of the major axis; you can estimate those from Figure 1.

CUME 330

Solutions

1 R_{25} 25 refers to a surface brightness limit in mag/arcsec^2. The standard definition is for the B mag limit.

2 a H_2 does not have a permanent dipole moment as a symmetric molecule so it does not have dipole transitions under normal cool/cold IS conditions.

CO is the next abundant molecule and has rotational transitions in the (sub) mm regime that are easily excited by collisions with (mostly) H_2 molecules even in cold gas. Hence CO is a tracer for H_2.

b Electronic transitions (like in atoms) – mostly in UV/optic
vibrational transitions – (N) IR
rotational transitions mm and sub mm regime.

3 a 30m telescope
$\nu = 115.271$ GHz $\rightarrow \lambda = 2.60$ mm
beam (radians): FWHM $\sim \dfrac{1.2\,\lambda}{D} = 21.''5$ $(1.04 \times 10^{-4}$ rad

This is very close to value given in paper.
It could be worse, depending e.g. on accuracy of outer edges of mirror, and the "illumination" of the primary by the ~~[illegible]~~ "horn" that connects / collects signal received to receiver.

3b Usually done as a check to make sure what bandpass & noise is received away from source.
So, like IR "beam switching". ~~[illegible]~~

c $D = 5.5$ Mpc
So $1''$ is equivalent to 4.85×10^{-6} radians or 26.7 pc
and $21'' \equiv 560$ pc.

d $N_{H_2} = 0.5 \times 10^{20}$ H_2 molecules / cm^2

beam size is $21''$ FWHM
So beam area (only out to half width) is
$\sim \pi (10''.5)^2 = 346.36$ sq. arcsec, or
2.46×10^5 pc^2
$= 2.34 \times 10^{42}$ cm^2.

$\rightarrow$ Total mass is $\underbrace{0.5 \times 10^{20}}_{N_{H_2}} \times \underbrace{2.34 \times 10^{42}}_{\text{area}} \times \underbrace{2 \times 1.66 \times 10^{-24}}_{m_{H_2}}$ g

$= 3.89 \times 10^{38}$ g $= 1.95 \times 10^5 M_\odot$

4a $V_{helio} = 46$ km/s for center.
Looking at Fig 1 & 2, we see that spectrum P8 is near $V_{helio} = 0$ km/s, so blue-shifted compared to center. That side is coming towards us, and galaxy rotates clock-wise, if spiral arms are trailing. However, if arms are leading, the upper side is further away from us and galaxy is rotating counter-clockwise.
So, you can't tell!

4b The points near P2 are closer to the minor axis than those near P8 and hence will show a V_{helio} closer to the systemic velocity (as the spectra in Fig 2 confirm)

4c General: $v_{circ} = \sqrt{\frac{GM(r)}{r}}$ for assumptions stated.

We know:

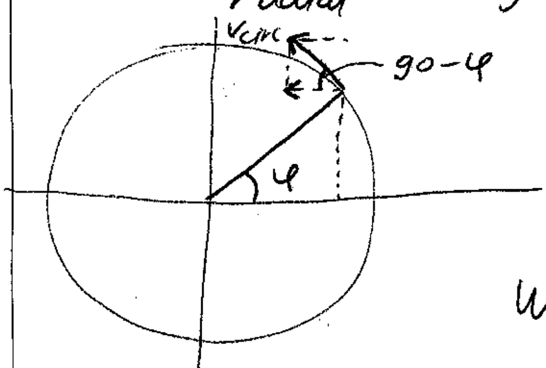
P8 is at $1.3\ R_{25}$. We can estimate R_{25} from Fig 1 and get $R_{25} \approx 5.9 \sim 9.5$ kpc

so our $r = (1.3)(9.5) = 12.4$ kpc

Estimate inclination angle from $\cos i \simeq \frac{\text{length minor axis}}{\text{length major axis}} = \frac{50\text{mm}}{61\text{mm}} \to i = 35^\circ$

Now we need to estimate V_{circ}.

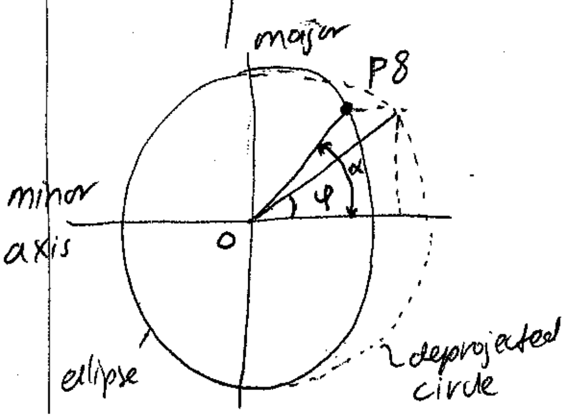
First consider for a galaxy seen edge-on (i.e. $i \equiv 90^\circ$) how v_{radial} changes with orientation:

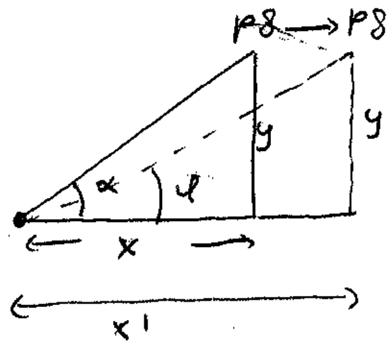


$$v_{obs}(\varphi) = V_{circ}\cos(90-\varphi)$$

$$= V_{circ}\sin\varphi$$

We need to determine φ for an inclined disk.





Measure (x, y) in Fig 1 (30 mm, 16 mm)

$$x' = \frac{x}{\cos i}$$

$$\tan\alpha = \frac{y}{x}$$

$$\tan\varphi = \frac{y}{x'}$$

$$= \frac{y\cos i}{x} \Rightarrow$$

$$\varphi \simeq 24^\circ$$

We have: $\left|V_{rad}(P8)\right| \approx \left|0 - 46\right| \frac{km}{s} = +46 \ \frac{km}{s}$

~~So~~ $V_{obs} = \left(V_{circ} \sin\varphi\right) \underbrace{\sin i}_{\text{projection factor due to inclination}}$

And $v_{circ} = \dfrac{v_{obs}}{\sin\varphi \sin i} = 197 \ \frac{km}{s}$

And $M(r) = \dfrac{v_{circ}^2 \, r}{G} = \dfrac{(197)^2 (10^5)^2 (12.4 \ kpc)(3.086 \times 10^{21})}{6.67 \times 10^{-8}} \, g$

$= 2.2 \times 10^{44} \ g$

$\simeq 1.1 \times 10^{11} \ M_\odot$