Rotation curves

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Rotation curves are obtained by measuring the circular velocity of hydrogen gas in disk galaxies. Neutral hydrogen gas (known as HI or "H-one" in astronomy lingo) emits radio waves at a particular wavelength $\lambda \simeq 21$ cm, corresponding to the hyperfine atomic transition. By measuring the Dopper shift of the measured radio signal, astronomers can measure the velocity of the gas.

The data files herein include rotation curves from the following galaxies:

- Dwarf galaxies from The HI Nearby Galaxy Survey (THINGS): *IC 2574, NGC 2366, Holmberg I, Holmberg II, DDO 53, M81dwB, DDO 154* [1]. These are small disk galaxies with very little stars and gas.
- Low surface brightness galaxies: *UGC 4325, F563-V2, F563-1, DDO 64, F568-3, UGC 5750, F583-4, F583-1* [2]. These are small-to-medium sized spiral galaxies with little stars and gas.

Rotation curves follow from equating the gravitational force and centripetal force

$$F_{\rm grav} = \frac{GmM_{\rm tot}}{r^2} = F_{\rm cent} = \frac{mv_c^2}{r} \tag{1}$$

where m represents the mass of an element of gas as radius r and $M_{\rm tot}(r)$ is the total mass of dark and visible matter that the gas is orbiting around. The latter is a function of radius r. Solving for the circular velocity v_c, we have

$$v_c(r) = \sqrt{\frac{GM_{\rm tot}(r)}{r}}\,. \tag{2}$$

The left-hand side is the circular velocity that is measured observationally.

The mass $M_{\rm tot}(r)$ represents the total mass that is enclosed within a radius r. There are three sources of mass that contribute to this term: stars, gas, and dark matter (DM). That is, we can write

$$M_{\rm tot}(r) = M_{\rm DM}(r) + M_{\rm stars}(r) + M_{\rm gas}(r)\,. \tag{3}$$

The gas mass is inferred by measuring the intensity of the 21 cm emission. The stellar mass is obtained through observations at other wavelengths and basically involves measuring how much starlight there is as a function of radius. In astronomy, the visible matter consisting of stars and gas is known as "baryons." The different components of the total rotation curve add together in quadrature

$$v_c^2 = v_{\rm DM}^2 + v_{\rm gas}^2 + v_{\rm stars}^2 \tag{4}$$

where

$$v_{\rm DM} = \sqrt{\frac{GM_{\rm DM}(r)}{r}}\,, \qquad v_{\rm gas} = \sqrt{\frac{GM_{\rm gas}(r)}{r}}\,, \qquad v_{\rm stars} = \sqrt{\frac{GM_{\rm stars}(r)}{r}} \tag{5}$$

If the goal is to figure out the DM mass $M_{\rm DM}(r)$, the contributions to the rotation curve from baryons need to be subtracted off from the measured circular velocity.

Every galaxy has two files:

- The file `RotationCurve_galaxy.csv` lists data points (radius r, circular velocity v_c, error on circular velocity δv_c) for each galaxy. In some galaxies, the quoted errors are very small and have been underestimated. It is suggested to include a systematic error at the level of 5% of the last measured velocity point.

- The file `RotationCurve_baryons_galaxy.csv` lists (radius r, gas velocity $v_{\rm gas}$, stellar velocity $v_{\rm stars}$), which is the contribution to the rotation curve from baryons. Note that the radius points r in the two data files are not the same.[1]

There is an additional complication due to the fact that the mass in stars is not well-known. This is because what is measured is the stellar *light*, which is predominantly from larger and bright stars, while the stellar *mass* is mostly made up of smaller and dimmer stars that are much more numerous. Hence, it is standard to introduce an additional fudge factor Υ_*, known as the mass-to-light ratio, as follows

$$v_c^2 = v_{\rm DM}^2 + v_{\rm gas}^2 + \Upsilon_* v_{\rm stars}^2\,. \tag{6}$$

Typically, Υ_* may vary from 1 by a factor of 2 (i.e., between $0.5-2$). The uncertainty in Υ_* is typically the largest uncertainty in rotation curve studies.

References

[1] S. H. Oh, W. J. G. de Blok, E. Brinks, F. Walter and R. C. Kennicutt, Jr, Astron. J. **141**, 193 (2011) [arXiv:1011.0899 [astro-ph.CO]].

[1] For some data points, the quoted value of $v_{\rm gas}$ or $v_{\rm stars}$ is negative. In these cases, the velocity is not really negative, but rather the velocity-*squared* is negative. This means that the value of $v_{\rm gas}^2$ or $v_{\rm stars}^2$ must be *subtracted* in Eq. (4). Such a situation occurs for a complicated baryon distributions.

[2] R. Kuzio de Naray, S. S. McGaugh and W. J. G. de Blok, Astrophys. J. **676**, 920 (2008) [arXiv:0712.0860 [astro-ph]].