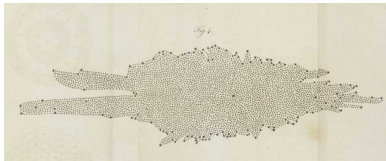


# The Milky Way

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## I. Attempts to survey

### I.1 Herschel



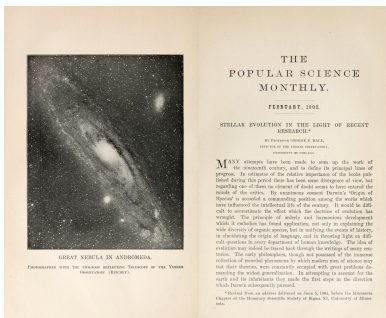
Herschel's 1785 map of the galaxy.

doi: 10.1098/rstl.1785.0012

Phil. Trans. R. Soc. Lond. 1785 vol. 75

213-266

Incorrect assumptions lead to this model of the galaxy, where our sun was roughly near the center. We can't see all the stars in our galaxy due to interstellar dust.



Andromeda as seen in 1902.

[Popular Science Monthly](#)

### The Great Debate

April 26 1920

Harlow Shapley and Heber Curtis

→ How big is the Milky Way (and the universe)

Write up: [Bulletin of the National Research Council](#)

### Globular Cluster

### Globular Cluster

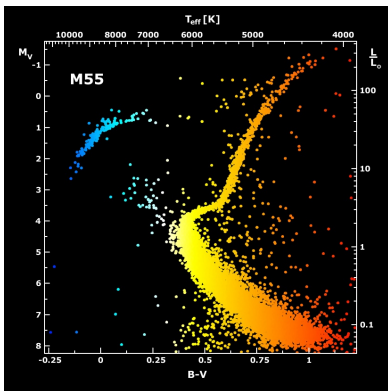
A dense cluster of old stars.

The stars contained within are gravitationally bound to each other.



Messier 68, a globular cluster. Might have  $10^6$  stars within a small (30 pc) diameter.

[ESA/Hubble & NASA](#)

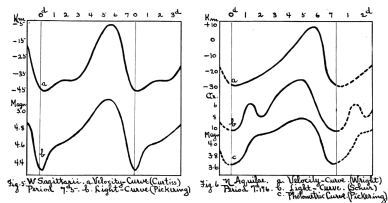


HR Diagram for a globular cluster (M-55)

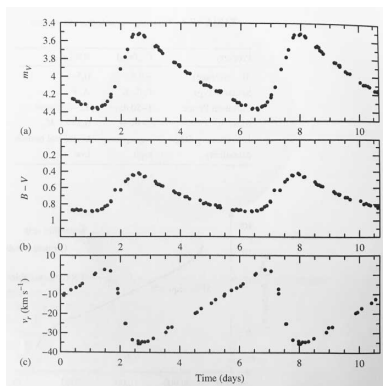
<https://apod.nasa.gov/apod/ap010223.html>

## Variable Stars

### Cepheids



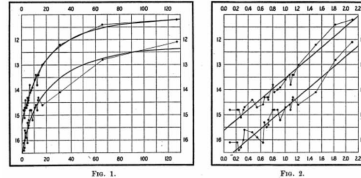
Brightness of some stars was found to be periodic.



Ryden & Peterson Fig 17.7

TABLE I.  
 PERIODS OF VARIABLE STARS IN THE SMALL MAGELLANIC CLOUD.

H.	Max.	Min.	Epoch.	Period.	Err. P.	Err. M.	H.	Max.	Min.	Epoch.	Period.	Err. P.	Err. M.
1403	14.8	16.1	0.02	1.23336	-0.6	-0.5	1400	14.1	14.8	4.0	6.550	+0.2	-0.3
1436	14.8	16.4	0.02	1.6637	-0.3	+0.1	1402	14.0	14.8	4.8	7.483	+0.2	-0.2
1446	14.8	16.4	1.38	1.7620	-0.3	+0.1	1374	13.9	15.2	6.0	8.397	+0.2	-0.3
1506	15.1	16.3	1.08	1.8702	+0.1	+0.1	818	13.3	14.7	4.0	10.336	0.0	0.0
1413	14.7	15.0	0.35	2.17332	-0.2	-0.2	1670	13.4	14.6	11.0	11.645	0.0	0.0
1469	14.4	15.7	0.90	2.923	-0.3	-0.1	1365	13.8	14.8	5.6	12.417	+0.4	+0.2
1422	14.7	15.0	0.6	3.501	+0.2	+0.2	1357	13.4	14.4	4.0	13.08	+0.1	-0.1
842	14.6	16.1	2.81	4.2807	+0.3	+0.6	827	13.4	14.2	11.6	13.47	+0.1	-0.2
1425	14.2	15.2	2.8	4.547	0.0	-0.1	829	13.6	14.9	13.0	16.75	-0.1	+0.3
1742	14.3	15.5	0.95	4.9866	+0.1	+0.2	823	12.2	14.1	2.9	31.94	-0.3	+0.4
1046	14.4	15.4	4.30	5.311	+0.3	+0.1	824	11.4	12.8	4.	65.8	-0.4	-0.3
1649	14.2	15.2	3.95	5.323	+0.2	-0.3	821	11.2	12.1	97.	127.0	-0.1	-0.4
1468	13.8	14.8	0.6	6.2926	-0.2	-0.4							



"A straight line can readily be drawn..."

[Periods of 25 Variable Stars in the Small Magellanic Cloud. Leavitt, Henrietta S.; Pickering, Edward C.; Harvard College Observatory Circular, vol. 173, pp.1-3](#)

[Periods of 25 Variable Stars in the Small Magellanic Cloud. Leavitt, Henrietta S.; Pickering, Edward C.; Harvard College Observatory Circular, vol. 173, pp.1-3](#)

Absolute magnitude is related to period:

$$\bar{M}_V = -2.76 \log\left(\frac{P}{10 \text{ days}}\right) - 4.16 \quad (1)$$

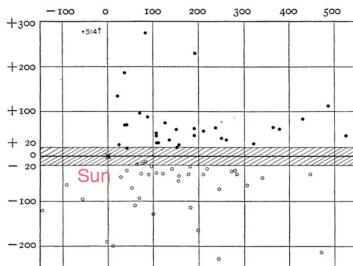
where  $\bar{M}_V$  is the absolute magnitude in the  $V$  band, measured over one complete period.

With this relation, if we know  $\bar{M}$  and  $m$ , then we can get distance,  $d$ .

$$M = m - 5 \log\left(\frac{d}{10 \text{ pc}}\right) \quad (2)$$

Obtaining this relationship requires knowing the distance to at least a few Cepheids. Parallax can get us a few.

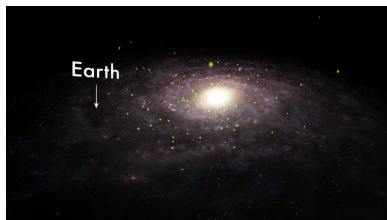
### Shapley's Map



The realization was that we are not in the center of the globular cluster distribution. The center is 'over there'. Shapley didn't account for dust, so his Milky way was about twice as big.

[Astrophysical Journal, 48, 154-181 \(1918\).](#)

Globular Clusters - more near the center.



The known Globular Clusters around our Milky Way

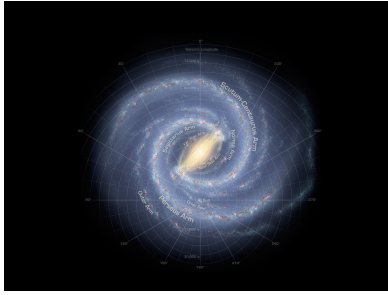
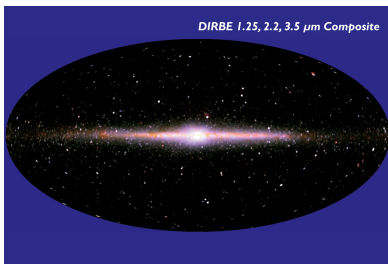


image by: [NASA/Adler/U. Chicago/Wesleyan/JPL-Caltech](#)

## 2. Milky Way Structure

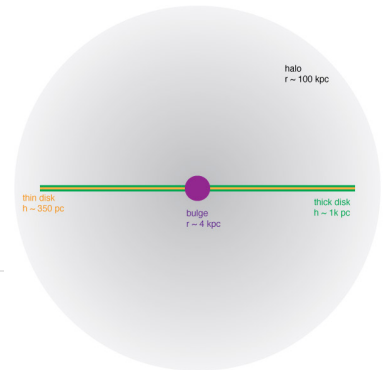


NASA, GSFC, COBE

False-color image of the near-infrared sky as seen by the DIRBE. Data at 1.25, 2.2, and 3.5  $\mu\text{m}$  wavelengths are represented respectively as blue, green and red colors. The image is presented in Galactic coordinates, with the plane of the Milky Way Galaxy horizontal across the middle and the Galactic center at the center. The dominant sources of light at these wavelengths are stars within our Galaxy. The image shows both the thin disk and central bulge populations of stars in our spiral galaxy. Our Sun, much closer to us than any other star, lies in the disk (which is why the disk appears edge-on to us) at a distance of about 28,000 light years from the center. The image is redder in directions where there is more dust between the stars absorbing starlight from distant stars. This absorption is so strong at visible wavelengths that the central part of the Milky Way cannot be seen. DIRBE data will facilitate studies of the content, energetics and large scale structure of the Galaxy, as

well as the nature and distribution of dust within the Solar System. The data also will be studied for evidence of a faint, uniform infrared background, the residual radiation from the first stars and galaxies formed following the Big Bang.

### 2.2 Thin & Thick disks



Schematic showing the main features: two disks and two spherical elements: bulge and halo.

Thin disk:

$$M: 6 \times 10^{10} M_{\odot}$$

$$\text{form: } e^{-z/h}$$

$$h \sim 0.350 \text{ kpc}$$

$$[\text{Fe}/\text{H}]: -0.5 \text{ to } +0.3$$

Thick disk:

$$M: 0.2\text{-}0.4 \times 10^{10} M_{\odot}$$

$$\text{form: } e^{-z/h}$$

$$h \sim 1 \text{ kpc}$$

$$[\text{Fe}/\text{H}]: -2.2 \text{ to } -0.5$$

### Metallicity

The ratio of Fe to H in the spectra of stars can be used to quantify a star.

$$[\text{Fe}/\text{H}] \equiv \log_{10} \left[ \frac{(N_{\text{Fe}}/N_{\text{H}})_{\text{star}}}{(N_{\text{Fe}}/N_{\text{H}})_{\text{sun}}} \right] \quad (3)$$

This is called the **metallicity**. ( $N_{Fe}$  and  $N_H$  are the number of Iron and Hydrogen atoms atoms.) Stars with the same proportion as the sun, will have values of  $[Fe/H] = 0$ . More metal rich stars have higher positive values. Less metal rich stars have negative values.

In general, younger stars will have higher metallicity than older stars.

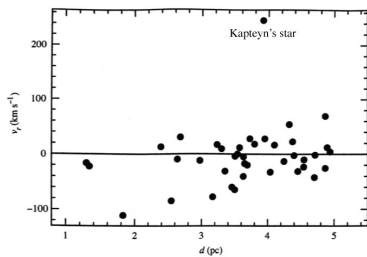
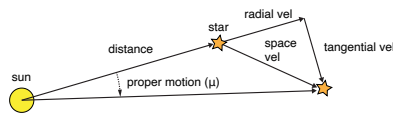
### 2.3 Milky way stats

- 200 Billion Stars
- Type: Barred spiral galaxy
- Diameter: 100–180 kly (31–55 kpc)
- Thickness of thin stellar disk: 2 kly (0.6 kpc)
- Oldest known star  $\geq 13.7$  Gyr
- Whole thing is moving at 600 km per second w.r.t the extragalactic frame of reference

And our place in it:

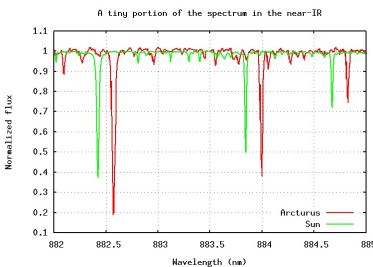
- Distance to center:  $26.4 \pm 1.0$  kly ( $8.09 \pm 0.31$  kpc)
- Sun's galactic rotation period: 240 Myr

### 3. Motion of Stars



Radial velocity:  $v_r$ . Measured using doppler shift of the star's absorption lines.

Ryden & Peterson, Fig 19.10

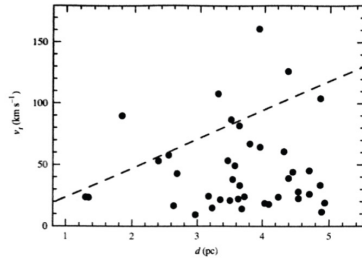


<http://spiff.rit.edu/classes/phys301/lectures/doppler/doppler.html>

Tangential velocity:  $v_t$ . Measured using proper motion,  $\mu$  and distance  $d$ .

$$\mu = \frac{v_t}{d} \quad (4)$$

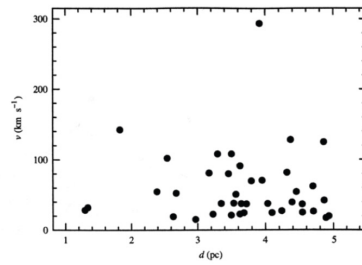
(in the small angle limit)



Ryden & Peterson, Fig 19.11



[http://www.backyardastronomer.com/ccd/Barnard\\_Mortfield\\_Cancelli\\_crop\\_labels1.gif](http://www.backyardastronomer.com/ccd/Barnard_Mortfield_Cancelli_crop_labels1.gif)

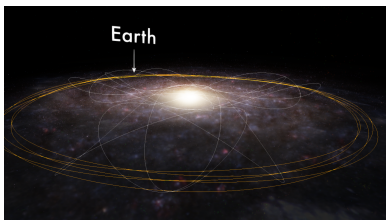


Space motion is the resultant of the radial and tangential velocities:

$$v = \sqrt{v_r^2 + v_t^2} \quad (5)$$

Space motion

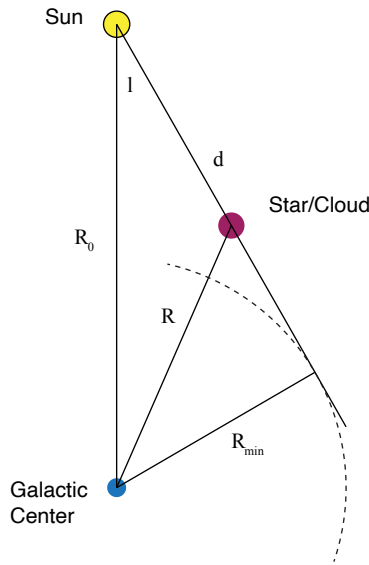
Ryden & Peterson, Fig 19.12



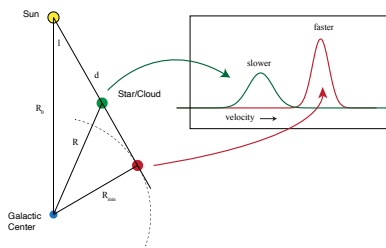
Two stars (sun = orange, Kapteyn's Star = white)

### 3.4 Measuring the rotation curve

We would like to know the distance  $R$ . Let's say we can't measure  $d$ , but we know  $R_0$  and  $l$ .

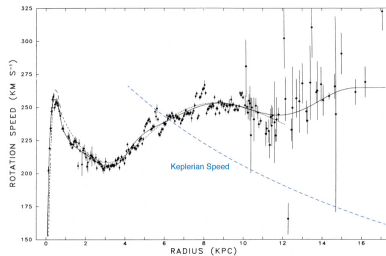


Geometry for measuring the  $R$  value for a star/cloud.



If we look along the line  $d$ , chances are likely there will be several gas clouds. Each with a different radial velocity. This difference is noted in the doppler shift of the light coming from some atomic process. For example,  $H_2$  molecules collide with CO molecules and create a radio emission with wavelengths of 2.6 and 1.3 mm, as measured in the lab. Deviations from these speeds are indicative of doppler shifts due to relative velocities.

We can measure these different velocities for the different gas clouds along the line of sight. The fastest will likely be closest to  $R_{min}$ . (this is a limitation of this measurement.)



[Astrophysical Journal, Part 1 \(ISSN 0004-637X\), vol. 295, Aug. 15, 1985, p. 422-428, 431-436.](#)

## 4. Dark Matter

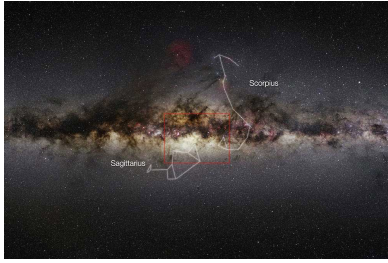
There's more stuff there that we just can't see, so it's called dark...

Astrophysicists and Cosmology folks are still figuring out what it is.

The leading candidate is WIMPs: Weakly Interacting Massive Particle. These are hypothetical particles that don't follow the same rules as the others in the standard model of particles physics.

## 5. The Galactic Center

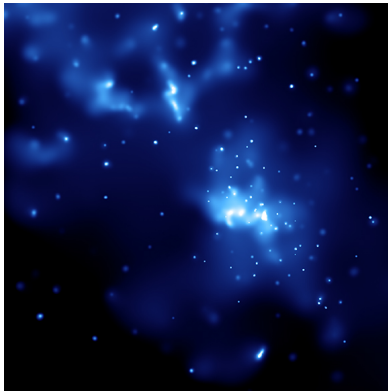
Can't see it too well



### 5.5 If we were closer...

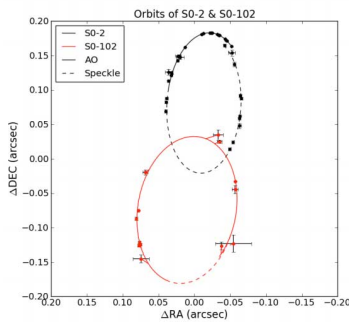
Let's move the solar system to half a parsec away from the galactic center.

- The nearest star would be ~ 1000 AU away
- The night sky would have  $10^6$  stars brighter than Sirius
- The total starlight would be ~ 200 times brighter than the moon
- Stars might collide!



Chandra X-ray Image of Sagittarius A\*

[NASA/CXC/Caltech/M.Muno et al.](http://www.nasa.gov/content/content_66203.html)



Based on the orbital parameters, we can get the semi-major axis of S2:

$$a_{S2} = \frac{r_p}{1 - e} = 1.4 \times 10^{14} \text{ m} \quad (6)$$

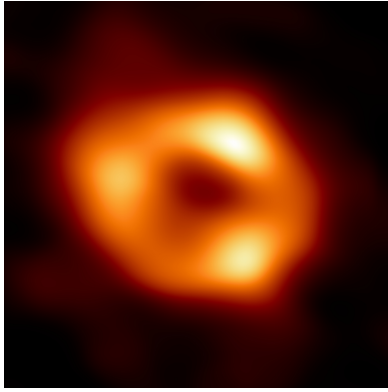
Based on Kepler's Third law, and a period of  $15.24 \pm 0.36$  yr:

$$\begin{aligned} M &= \frac{4\pi^2 a_{S2}^3}{GP^2} \\ &\simeq 7 \times 10^{36} \text{ kg} \\ &\simeq 3.5 \times 10^6 M_{\text{Sun}} \end{aligned} \quad (7)$$

The orbits of S0-2 (black) and S0-102 (red). The data points and the best fits are shown. Both stars orbit clockwise

<http://science.sciencemag.org/content/338/6103/84>

Image of Black Hole at the center of the Milky Way



First image of the black hole at the centre of the Milky Way

Credit: [EHT Collaboration](#):

**An Introduction to the EHT | Event Horizon Telescope**  
eh telescope



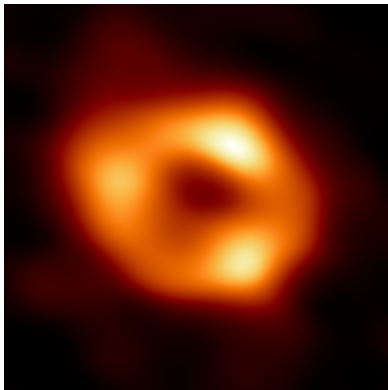
Watch on

## Light's Odyssey: The Journey from a Black Hole to Earth

ehtelelescope



Watch on



The Black hole at the center of the Milky Way, as imaged by the Event Horizon Telescope

[Ref](#)