THE MILKY WAY GALAXY

James Binney
Physics Department Oxford University

Keywords: Milky Way, galaxies

Contents

Summary

Our Galaxy is typical of the galaxies that dominate star formation in the present Universe. It is a barred spiral galaxy – a still-forming disc surrounds an old and barred spheroid. A massive black hole marks the center of the Galaxy. The (Our) Sun sits far out in the disc and in visible light. Our view of the Galaxy is limited by interstellar dust. Consequently, the large-scale structure of the Galaxy must be inferred from observations made at infrared and radio wavelengths. The central bar and spiral structure in the stellar disc, generate significant non-axisymmetric gravitational forces that make the gas disc and its embedded star formation strongly non-axisymmetric. Molecular hydrogen is more centrally concentrated than atomic hydrogen and much of it is contained in molecular clouds within which stars form. Probably all stars are formed in an association or cluster, and energy released by the more massive stars quickly disperses gas left over from their birth. This dispersal of residual gas usually leads to the dissolution of the association or cluster. The stellar disc can be decomposed to a thin disc, which comprises stars formed over most of the Galaxy's lifetime, and a thick disc, which contains only stars formed in about the Galaxy's first Gigayear. The Galaxy has two distinct populations of globular clusters, and an attendant host of dwarf spheroidal galaxies. Both globular clusters and dwarf spheroidal galaxies give rise to tidal streams. Globular clusters appear to contain no dark matter, while dwarf spheroidal galaxies are dominated by dark matter. Stars account for more than half of the

gravitational force that holds the Sun in its roughly circular orbit around the galactic center, but the rest is probably attributable to a roughly spherical halo made up of still undiscovered elementary particles.

1. Introduction

Galaxies vary enormously in size from objects that contain only100000 stars, to ones with hundreds of billions of stars. The smaller galaxies are much more numerous than the larger ones, but not by a sufficient factor to compensate for their lower luminosities. So, most of the luminosity in the Universe is contributed by galaxies that lie just below the top of the scale. The Sun lies in just such a galaxy, the *Milky Way* galaxy.

Galaxies can usefully be considered to be made up of two components: a *spheroid* and a *disc* (Figure 1). The spheroid is made up of stars that move around in a disorganized way, rather like a swarm of bees. Its name derives from its only moderately non-spherical shape. The disc is a highly flattened structure in which stars move in nearly circular orbits around the center and never go far from the system's equatorial plane. The *morphological type* of a galaxy is determined by the relative contributions of these two components to the system's total luminosity. *Early-type galaxies* are dominated by their spheroids: in the extreme case of an *elliptical galaxy* casual inspection reveals only a spheroid, although very precise measurements may reveal a disc deeply buried inside the spheroid. In the case of a very *late-type galaxy*, there may be no detectable bulge, only a disc.

Besides the relative importance of disc and bulge, early-and late-type galaxies differ in their rates of star formation and the mean age of their stars: early-type galaxies have little or no cold, dense gas from which stars can form, so their rates of star formation are small and nearly all their stars are old. Late-type galaxies possess cold, dense gas so they have on-going star formation and significant populations of young stars. In each batch of freshly formed stars, there will be both massive stars (masses up to $100M_\odot$, 100 times the mass of the Sun) and low-mass stars(below about $2M_\odot$). Massive stars are extremely luminous, blue and short-lived, while low-mass stars are long-lived, red and faint. Consequently, early-type galaxies are red and their brightness distributions are smooth because they are generated by enormous numbers of individually faint stars. Late-type galaxies, by contrast, are blue and their brightness distributions are patchy, because a scattering of extremely luminous stars can make a particular region much more luminous than another of equal size.

The Milky Way is a moderately late-type galaxy in which about 90% of the luminosity is contributed by the disc, while the center of the system is dominated by a spheroid that is often called the bulge–from the outside it would look something like the galaxy shown in the middle panel of Figure 1. The Sun sits quite near the rim of the luminous part of the disc, so the Galaxy appears as a band of stars across the sky, marking directions in which we see out into the disc (Figure 2). The bulge lies in the constellation Sagittarius in the southern sky.

The distance to the Galactic center is still not precisely known, but the best available value is now 8.3 kiloparsecs, roughly 25000 light years (Gillessen et al.2009). The disc has a mass $\sim 6\times10^{10} M_\odot$, while that of the bulge is $\sim 10^{10} M_\odot$ (Launhardt et al., 2002). Studies of the Milky Way frequently make use of *Galactic coordinates*, (l,b), for the celestial sphere; the *latitude* b is the angle between a line of sight and the Galactic plane, with positive values lying to the north of the plane. The longitude l is the angle between the projection of the line-of-sight into the plane and the direction to the Galactic center (Figure 3). Thus the Galactic center has coordinates $(l,b)=(0,0)$.

2. Recognition of the Size of the Milky Way

Since time immemorial our ancestors have been familiar with the Milky Way as a band of light that stretches right across the sky on a dark night. Galileo first showed that this band is constituted of myriads of faint stars, but it was less than a century ago that, astronomers finally grasped that the Milky Way is a galaxy like those that in the early 19th century had been catalogued in great numbers by the Herschels. Two problems were responsible for the delay in recognizing what the Milky Way really is: the usual difficulty of measuring astronomical distances, and a lack of awareness of the existence of an obscuring interstellar medium.

The central plane of the disc contains most of the Galaxy's supply of cold, star-forming gas. This gas is extremely heavily polluted by eject a from stars: if it were compressed to the density of air (i.e., by a factor $\sim 10^{21}$) one could see only a few cm through it because light is absorbed by particles of dust (a better name might be smoke) suspended in the gas. Even at the extremely low densities characteristic of interstellar space, we can see only of order a kiloparsec through this gas, which should be compared with the 8.3kpc to the Galactic center. Hence at optical wavelengths we cannot see through the disc to the bulge. This obscuration by dust strongly influenced the growth in our understanding of the Milky Way. In the first decades of the 20th century, before astronomers knew of interstellar dust, it was thought that we lived near the center of a disc of stars that was about 2 kpc in radius. The objects that we now know to be external galaxies were thought to lie within this disc, so the latter was thought to constitute the whole Universe–this world picture is called Kapteyn's Universe after the Dutch astronomer who led an international effort to map it. In the 1920s evidence for obscuration by interstellar dust mounted, and it was demonstrated that external galaxies lie far outside the bounds of Kapteyn's Universe. These two advances made it natural to interpret the Milky Way as an object similar to some external galaxies. The decisive step in this direction was taken in 1927 by another Dutch astronomer, Jan Oort, who interpreted the motions of nearby stars in terms of differential rotation within a disc of stars that is ~ 10 kpc in radius. A global view of the Galaxy was first obtained in the 1950s following the detection of hydrogen at radio frequencies (at a wavelength of 21cm) using technology that had been developed for radar in the Second World War: interstellar gas is almost transparent to radio waves, so by scanning the sky with radio telescopes in the Netherlands and Australia it was possible to study the large-scale structure of the Galactic disc. Normal stars cannot be usefully studied at radio wavelengths, so our first clear view of the Galactic bulge came in 1991 in near-infrared data taken by the COBE/DIRBE satellite. The angular resolution of the COBE/DIRBE data was poor $(\sim 0.5°)$ and a much sharper image was subsequently obtained from the 2 MASS infrared survey of the sky (Figure 4). In this picture one clearly sees the stellar disc and the bulge, and some dark wisps of obscuration by dust, which is very much weaker at near-infrared than at optical wavelengths, but not negligible.

Figure 1. Disc galaxies with spheroids of decreasing prominence. On the extreme left is the Sombrero galaxy, M104, which is dominated by its spheroid. In the center is M63 with a much smaller but clearly visible bulge. On the right is M33, which has no discernible spheroid. Credits: M104 – NASA and the Hubble Heritage Team (STScI/AURA); M63 copyright Şubaru Telescope, National Astronomical Observatory of Japan. All rights reserved. M33 –T.A. Rector (NRAO/AUI/NSF and NOAO/AURA/NSF) and M.Hanna (NOAO/AURA/NSF).

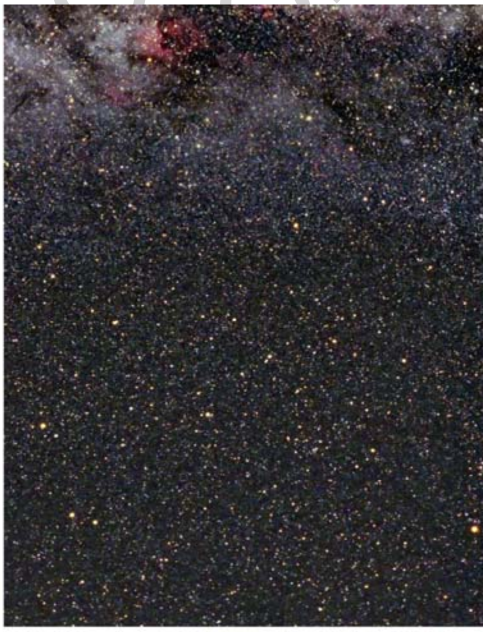

Figure 2. The Milky Way in visible light is a patchwork of regions made bright by myriads of stars, and regions blanked out by foreground dust. The concentration of stars towards the Galactic plane is evident, as is the decrease in star density as one moves

away from the Galactic Center, which is in the middle of the image. (Image courtesy of Axel Mellinger)

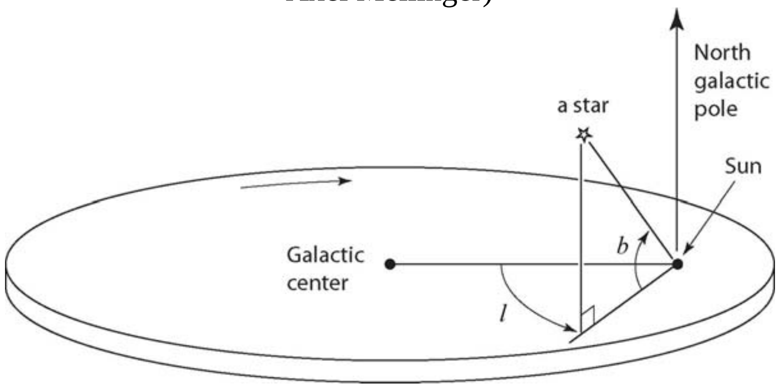

Figure 3. The definition of Galactic coordinates. (From Binney & Tremaine, 2008)

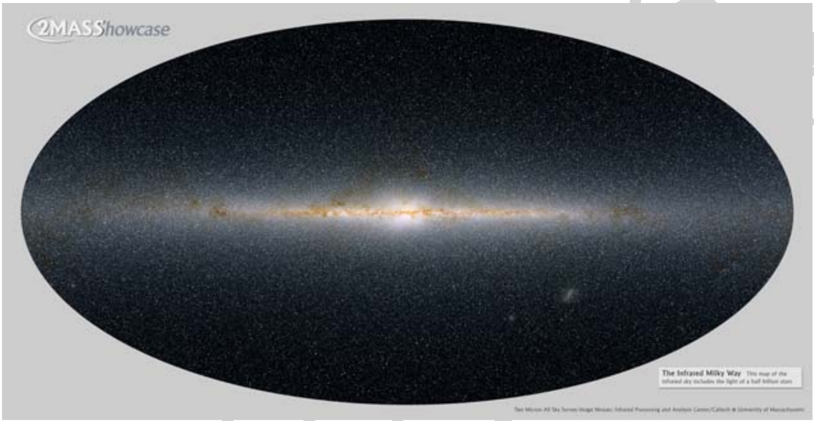

Figure 4. The Galaxy in near-infrared light. The whole sky is shown, so what is shown at extreme right and left is what lies behind your head as you look at the Galactic Center, which appears in the middle of the image. The light comes from myriads of stars, only a few of which are resolved by the telescope into points of light. Credit: Two-micron Survey Infrared Processing and Analysis Center/ Caltech & University of Massachusetts.

3. The Center

A black hole of mass $4.4\times10^6 M_\odot$ sits at the center of the Milky Way (Gillessen et al.2009). Weak radio and X-ray radiation emerges from its location, and it takes its name, Sgr A*, from the catalogue entry of the radio source that we now know is associated with the black hole. We know a black hole is there because we can study the motion of luminous stars as they orbit in its powerful gravitational field; a star called S2 has now been followed through one complete orbit around Sgr A* (Figure 5). The orbit is highly eccentric and accurately fitted by a Kepler ellipse, demonstrating that it is moving in the gravitational field of point mass.

A crucial distance from a black hole is the *Schwarzschild radius*, r_s, interior to which light is trapped by the hole's gravitational field. For Sgr A* $r_s = 10^7$ km. The closest that

S2 comes on its orbit is 2×10^{10} km, so although at this point it is moving at 6000kms^{-1}, relativistic effects are not large along this orbit.

S2 is one of the most luminous stars in a star cluster that surrounds Sgr A*, and it is young. It comes as a surprise to find young stars so close to Sgr A* because theory suggests that density inhomogeneities in a protostellar cloud could not grow into stars so near to a huge point mass.

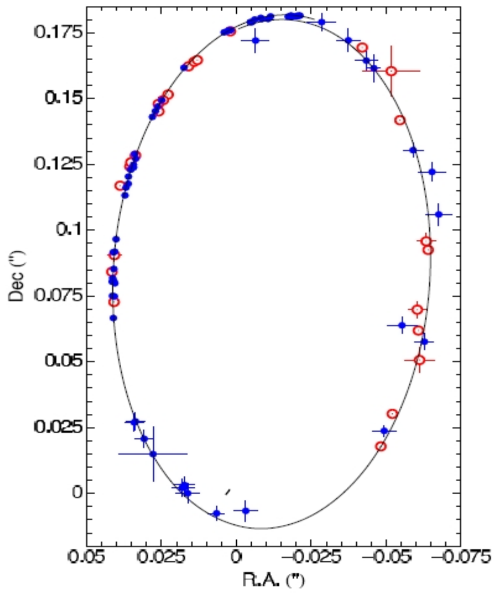

Figure 5. The orbit of S2 around the black hole that dominates the Galactic center. The orbit has a period of 15.2yr and the data points cover the period 1994–2008. The orbit's semi-major axis and eccentricity are 0.119arcsecand0.87. The data points in the upper left part of the orbit have tiny error bars because these are the most recent data and were obtained with the latest technology. (From Gillessen et al 2009).

-
-
-

Bibliography

Ahmed, Z.; Akerib, D.S.; Arrenberg, S.; Bailey, C.N.; Balakishiyeva, D.; Baudis, L.; Bauer, D.A.; Brink, P.L.; Bruch, T.; Bunker, R.; Cabrera, B.; Caldwell, D.O.; Cooley, J.; Cushman, P.; Daal, M.; DeJongh, F.; Dragowsky, M.R.; Duong, L.; Fallows, S.; Figueroa-Feliciano, E.; Filippini, J.; Fritts,

M.; Golwala, S.R.; Grant, D.R.; Hall, J.; Hennings-Yeomans, R.; Hertel, S.A.; Holmgren, D.; Hsu, L.; Huber, M.E.; Kamaev, O.; Kiveni, M.; Kos, M.; Leman, S.W.; Mahapatra, R.; Mandic, V.; McCarthy, K.A.; Mirabolfathi, N.; Moore, D.; Nelson, H.; Ogburn, R.W.; Phipps, A.; Pyle, M.; Qiu, X.; Ramberg, E.; Rau, W.; Reisetter, A.; Saab, T.; Sadoulet, B.; Sander, J.; Schnee, R.W.; Seitz, D.N.; Serfass, B.; Sundqvist, K.M.; Tarka, M.; Wikus, P.; Yellin, S.; Yoo, J.; Young, B.A. and Zhang J., (2010). *Results from a Low-Energy Analysis of the CDMS II Germanium Data*, PhRvL 106, 1302 [Results of recent dark matter search]

Ballero, S.K., Matteucci, F., Origlia, L. & Rich, R.M., 2007, A&A, 467, 123 *Formation and evolution of the Galactic bulge: constraints from stellar abundances* [Estimates of the ages of stars in the bulge]

Belokurov, V.; Zucker, D. B.; Evans, N. W.; Gilmore, G.; Vidrih, S.; Bramich, D. M.; Newberg, H. J.; Wyse, R. F. G.; Irwin, M. J.; Fellhauer, M.; Hewett, P. C.; Walton, N. A.; Wilkinson, M. I.; Cole, N.; Yanny, B.; Rockosi, C. M.; Beers, T. C.; Bell, E. F.; Brinkmann, J.; Ivezi, .; Lupton, R. (2006)

The Field of Streams: Sagittarius and Its Siblings ApJ, 642, L137 [The study that first showed the Field of Streams]

Binney J. & Merrifield M. (1998) Galactic Astronomy, 796 pp. Princeton, NJ, USA

Binney J. & Tremaine S. (2008) Galactic Dynamics, 885 pp. Princeton, NJ, USA

Bland-Hawthorn, J., & Cohen, M., 2003, ApJ, 582, 246 *The Large-Scale Bipolar Wind in the Galactic Center* [Evidence from X-ray emission that gas is flowing out from the nuclear disc]

Chung, A., van Gorkom, J.H., Kenney, J.D.P., Crowl, H. & Vollmer, B., 2009, AJ, 138, 1741 *VLA Imaging of Virgo Spirals in Atomic Gas* [Evidence that star formation ceases soon after a galaxy falls into a cluster, where it can no longer accrete gas]

Fux, R., 1999, A&A, 345, 787 *3D self-consistent N-body barred models of the Milky Way* [A dynamical model of gas in the Galaxy]

Gillessen, S.; Eisenhauer, F.; Fritz, T. K.; Bartko, H.; Dodds-Eden, K.; Pfuhl, O.; Ott, T.; Genzel, R. (2009) The Orbit of the Star S2 Around SGR A* from Very Large Telescope and Keck Data ApJL 707, L114 [Recent determination of the distance to the Galactic center]

Gilmore, G. & Reid, I.N., 1983, MNRAS, 202, 1025 *New light on faint stars. III - Galactic structure towards the South Pole and the Galactic thick disc* [Discovery of the Galaxy's thick disk]

Holmberg, J. & Flynn, C., 2000, MNRAS, 313, 209 *The local density of matter mapped by Hipparcos* [A determination of the local density in the Galaxy]

Klypin, A., Zhao, H-S. & Somerville, R.S., 2002, ApJ, 573, 597 *CDM-based Models for the Milky Way and M31* [Parameters of the Galaxy's dark halo]

Launhardt, R., Zylka, R., & Mezger, P.G., 2002, A&A, 384, 112 *The nuclear bulge of the Galaxy* [Parameters of the Galaxy's bulge and nuclear disk]

Malhotra, S., 1995, ApJ, 448, 138 The Vertical Distribution and Kinematics of H i and Mass Models of the Galactic Disk [Determination of the terminal velocities of gas in the disc]

McMillan, P.J. & Binney, J.J. (2010) The uncertainty in Galactic parameters MNRAS, 402, 934 [Determination of the local rotational velocity in the Galaxy]

Navarro, J.F., Frenk, C.S. & White, 1997, ApJ, 490, 493 A Universal Density Profile from Hierarchical Clustering [Widely adopted parameterization of the darlk halo density profile]

Odenkirchen, M.; Grebel, E.K.; Dehnen, W.; Rix, H.-W.; Yanny, B.; Newberg, H.J.; Rockosi, C.M.; Mart??nez-Delgado, D.; Brinkmann, J.; Pier, J.R. (2003) The Extended Tails of Palomar 5: A 10?? Arc of Globular Cluster Tidal Debris AJ, 126, 2385 [A study of the disruption of the globular cluster Palomar 5 by the Galaxy's gravitational field]

Reid, M. J.; Menten, K. M.; Zheng, X. W.; Brunthaler, A.; Moscadelli, L.; Xu, Y.; Zhang, B.; Sato, M.; Honma, M.; Hirota, T.; Hachisuka, K.; Choi, Y. K.; Moellenbrock, G. A.; Bartkiewicz, A. (2009) Trigonometric Parallaxes of Massive Star-Forming Regions ApJ, 700, 137 [Measurements of the parallaxes of star-forming regions that lie several kiloparsecs from the Sun]

Robin, A.C., Reylé, C., Derrière, S. & Picaud, S., 2003, A&A, 409, 523 A synthetic view on structure and evolution of the Milky Way [Determination of the brightness profile of the disk]

Russeil, D., 2003, A&A, 397, 133 *Star-forming complexes and the spiral structure of our Galaxy* [Spiral-arm structure]

Schönrich, R. & Binney, J., 2009, MNRAS, 399, 1145 *Origin and structure of the Galactic disc(s)* [A model of the chemical and dynamical evolution of the Galactic disk]

Sellwood, J.A. & Binney, J., 2002, MNRAS, 336, 785 *Radial mixing in galactic discs* [Demonst6ration that a major effect of spiral structure is to cause stars to migrate radially by several kiloparsecs]

Stanek, K.Z., Mateo, M., Udalski, A., Szymanski, M., Kaluzny, J. & Kubiak, M., 1994, ApJ, 429, L73 Color-magnitude diagram distribution of the bulge red clump stars: Evidence for the galactic bar [Evidence that stars seen in the bulge to the left of the Galactic center are closer than those seen on the right, which confirmed that the bulge is barred rather than axisymmetric]

Strickland, D.K., Heckman T.M., Colbert E.J.M., Hoopes C.G., Weaver K.A., 2004, ApJS, 151, 193 *A High Spatial Resolution X-Ray and H alpha Study of Hot Gas in the Halos of Star-forming Disk Galaxies* [Evidence of gas ouflows from other galaxies]

Strong, A. W.; Bloemen, J. B. G. M.; Dame, T. M.; Grenier, I. A.; Hermsen, W.; Lebrun, F.; Nyman, L.-A.; Pollock, A. M. T.; Thaddeus, P. (1988) The radial distribution of galactic gamma rays A&A, 207, 1 [An estimate of the masses of molecular clouds]

vanAlbada, T.S., Bahcall, J.N., Begeman, K. & Sancisi, R., 1985, ApJ, 295, 305 *Distribution of dark matter in the spiral galaxy NGC 3198* [The decisive evidence that disc galaxies have massive dark halos]

Walker, M.G.; Mateo, M.; Olszewski, E.W.; Gnedin, O.Y.; Wang, X.; Sen, B.; Woodroofe, M. (2007) Velocity Dispersion Profiles of Seven Dwarf Spheroidal Galaxies ApJ, 667, 53 [Evidence that dwarf spheroidal galaxies are dominated by extended distributios of dark matter]

Zwicky, F. 1933. Helv. Phys. Acta 6 110 Die Rotverschiebung von extragalaktischen Nebeln [The first suggestion that clusters of galaxies contain much more mass than that contained in their stars]

Biographical Sketch

James Binney earned his BA degree at the University of Cambridge in 1971.After two semesters in Freiburg i Breisgau he wrote a doctoral thesis on the formation of galaxies in Oxford, graduating in 1975. He was a Lindemann Fellow at Princeton University 1975/6, a Fellow by Examination of Magdalen College Oxford 1975–1979, a Visiting Assistant Professor at Princeton University 1979–1981 and has been on the Faculty of Oxford University and a Fellow of Merton College since 1981. He was awarded the Maxwell Prize for 1986 by the Institute of Physics and the Brouwer Award for 2003 by the American Astronomical Society. In 2000 he was elected a Fellow of the Royal Society of London. His books include *Galactic Dynamics* with Scott Tremaine (Princeton University Press 1987 & 2008) and *Galactic Astronomy* with Michael Merrifield (PrincetonUniversityPress1998).

His research concerns the structure, dynamics and formation of galaxies.