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Excerpt
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Part I

Basic Phenomenology

1 Scales

A piece of writing that best captures the beauty and mystery surrounding the dynamics of galaxies can be found in chapter 7 of the first volume of *The Feynman Lectures on Physics*.[1] There, in a few simple sentences and by means of a picture of a globular cluster and a spiral galaxy, we are rapidly brought to the scales and structure of the systems involved and to the underlying limits that our physical knowledge must recognize. We are told that gravitation is the prime actor, stars rarely collide, and angular momentum leads to a contraction in a plane, but we are also reminded of the facts that "of course we cannot prove that the law here is precisely inverse square," "what determines the shape of these galaxies has not been worked out," and that we are dealing with systems that are enormously complex.

Approximately four decades earlier, through a decisive distance measurement, some nebulae had been recognized as huge systems millions of light years away; those were nearby galaxies, and galaxies were thus found to be the visible building blocks of the Universe. If we examine that discovery,[2] we see that modern cosmology and quantum mechanics were developed at approximately the same time and well after the formulation of general relativity;[3] they were also developed well after the basic equations that govern the motion of a self-gravitating stellar system were studied by Jeans.[4]

Thus many of the objects that had been studied and cataloged for more than a century, through the patient work of Messier, the Herschels, and Dreyer, turned out to be galaxies.[5] Now, more than eight decades after their discovery, great progress has been made, and galaxies have been observed out to distances that are measured in billions of light years, almost at the end of the Universe (or, rather, at its beginning; Fig. 1.1).[6]

Typical masses of galaxies are in the range 10^9 to $10^{12}\,M_\odot$, where one solar mass is $1\,M_\odot \approx 2\times10^{33}$ g. Their linear scales are in the range 1 to 100 kpc (kpc is a kiloparsec), where 1 kpc $\approx 3.1\times10^{21}$ cm. Velocities inside a galaxy are in the range 50 to 500 km s^{-1}, so typical dynamical time scales are 10^8 to 10^9 yr (note that 1 km s$^{-1}\times10^9$ yr ≈ 1.02 kpc). We recall that the Hubble time, that is, the age of the Universe, is $\approx 10^{10}$ yr. The Milky Way galaxy has a mass estimated to be close to $2\times10^{11}\,M_\odot$. The Sun is located at ≈ 8 kpc from the galactic center, and the rotation velocity around the galactic center in the solar neighborhood is ≈ 220 km s^{-1}. The mass density in the solar neighborhood is ≈ 6 protons per cubic centimeter, whereas the local density of the Galaxy disk is $\approx 50\,M_\odot$ pc^{-2}, which is close to that of an ordinary sheet of paper. The local energy densities (e.g., turbulent, magnetic, etc.) are close to 1 eV cm^{-3}, except for the overall rotation-energy density, which is close to 1 keV cm^{-3}; we recall that 1 eV $\approx 1.6\times10^{-12}$ erg.

Fig. 1.1. The Hubble Ultra Deep Field [credit: NASA, ESA, S. Beckwith (STScI), and the HUDF Team; see also Beckwith, S. V. W., Stiavelli, M., et al. 2006. *Astron. J.*, **132**, 1729]. This image was taken by observation with the *Hubble Space Telescope* in a 1-million-second exposure and contains an estimated 10,000 galaxies in a region one-tenth the diameter of the full Moon, with objects detected down to the 30th magnitude. A large fraction of these galaxies are at a redshift larger than unity, some at $z > 7$, as confirmed by spectroscopic observations with large telescopes from the ground; thus some galaxies existed earlier than 1 billion years after the Big Bang.

All these should be taken as scales for objects called *galaxies*. In reality, gravitation acts and isolates clumps of matter on all scales. Thus we can recognize well-defined subsystems inside galaxies; the largest of these subsystems are globular clusters and giant molecular clouds (with masses in the range 10^4 to $10^6 M_\odot$) down to open clusters and multiple stellar systems. In our Galaxy there are more than 150 globular clusters with a spheroidal space distribution. Elliptical galaxies may host thousands of globular clusters.[7]

On larger scales, galaxies are often found in groups or in clusters of galaxies. The Local Group contains more than thirty galaxies (M31, i.e., the Andromeda galaxy,[8] and the Milky Way galaxy[9] are the largest) spread out on the scale of a few million light years. The Large

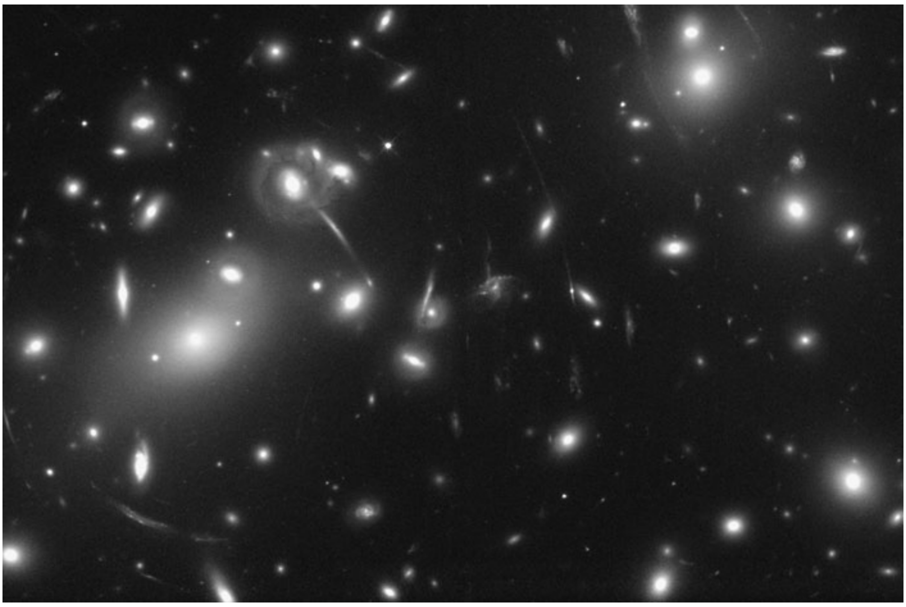

Fig. 1.2. Gravitational lensing by an intervening cluster of galaxies [credit: NASA, ESA, Richard Ellis (Caltech), and Jean-Paul Kneib (Observatoire Midi-Pyrenees, France)]. The mass of Abell 2218 distorts the images of distant galaxies into arcs and arclets.

Magellanic Cloud is at a distance of ≈ 50 kpc, and M31 is at a distance of ≈ 800 kpc. The Local Group lies at the outskirts of the Virgo cluster, which contains more than 2,000 galaxies; the center of the Virgo cluster is usually associated with the giant elliptical galaxy M87, ≈ 15 Mpc away from us.[10] Clusters of galaxies thus contain large amounts of matter, which often acts as a gravitational lens for the light coming from more distant galaxies[11] (Fig. 1.2); a large fraction of their visible mass is in the form of a hot intergalactic medium that is confined in the potential well of the cluster and observed by X-ray telescopes.[12] Clusters are thus a very active environment in which galaxy-galaxy and galaxy-intracluster medium interactions participate in their long-term evolution. A striking case is that of a distant galaxy cluster that turned out to be the brightest X-ray cluster known (with $L_X \approx 2 \times 10^{46}$ erg s^{-1}) at the time of its discovery,[13] for which the energy loss that is due to X-rays was thought to induce an inflow of intergalactic matter toward its central regions at a rate estimated to exceed $3 \times 10^3 \, M_\odot$ yr^{-1}.

The visible mass in galaxies is primarily in the form of stars. Gas, even in the case of the so-called late-type spirals that have the largest gas content, does not contribute more than a few percent of the total mass. However, because the various forms of matter have different spatial distributions, it should be kept in mind that, at some locations, the gas content can be significant. For example, in the outer disks of spiral galaxies, the gas-to-star surface density ratio can easily exceed 15 percent. In the case of elliptical galaxies, traditionally described as gas-free systems, there are examples, such as NGC 4636, in which almost $10^{11} \, M_\odot$ (i.e., ≈ 10 percent of the estimated stellar mass) is in the form of hot, X-ray-emitting plasma; this hot corona occupies a volume larger than that of the luminous component. This point about the forms of mass distribution is further complicated by the fact that we have evidence for the presence of dark

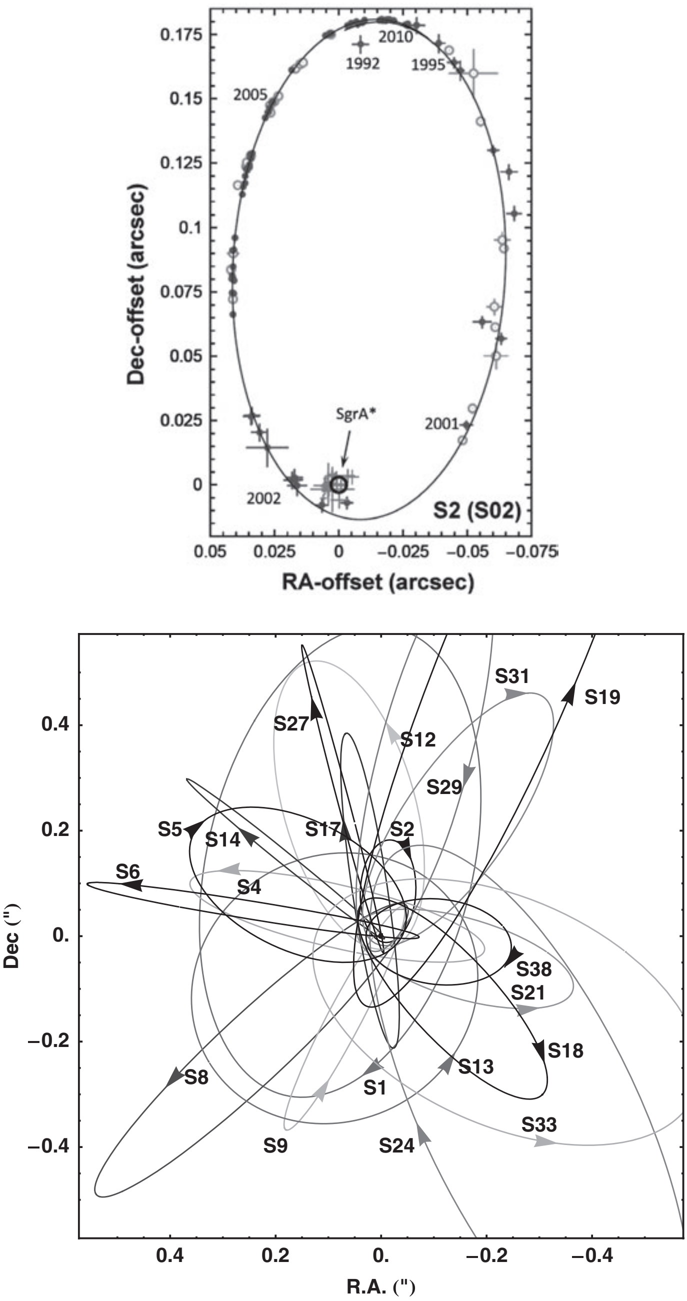

Fig. 1.3. *Top*: The elliptical orbit of the star S2 in the vicinity of Sgr A* at the Galactic Center (Genzel, R., Eisenhauer, F., Gillessen, S. "The Galactic Center massive black hole and nuclear star cluster," 2010. *Rev. Mod. Phys.*, **82**, 3121; © 2010 by the American Physical Society). The positions in the sky were obtained in the period 1992–2010 by combining data from NTT/VLT with others from *Keck*. The pericenter of S2 is ≈ 125 AU (astronomical units), that is, ≈ 17 light hours from a compact object with mass $\approx 4 \times 10^6\, M_\odot$. *Bottom*: A set of twenty star orbits in the vicinity of Sgr A* at the Galactic Center (Gillessen, S., Eisenhauer, F., et al. 2009. "Monitoring stellar orbits around the massive black hole in the Galactic Center," *Astrophys. J.*, **692**, 1075; reproduced by permission of the AAS).

matter, which may be in a form that is neither stellar nor gaseous. Conservative estimates suggest that typically the amount of dark matter in galaxies is close to the amount of visible matter, if referred to the volume in which the visible matter is observed. On bigger volumes, the relative amount of dark matter may be significantly larger. The appropriate numbers for these distributions are very important for proper modeling, especially because the stellar component and, most likely, the dark-matter component are collisionless and dissipationless, whereas the gas is a dissipative subsystem. The cold gas in galaxy disks is dissipative because of inelastic cloud-cloud collisions that occur on a very short time scale, whereas the hot gas in bright elliptical galaxies dissipates by means of radiative cooling.

A systematic study of galactic nuclei and cores has led to dramatic evidence for the presence of supermassive black holes even in inactive galaxies,[14] with masses in the range 10^6 to $10^9\, M_\odot$. In fact, a beautiful study of stellar orbits[15] has shown that our Galaxy hosts a central black hole with a mass of $\approx 4 \times 10^6\, M_\odot$ (Fig. 1.3). To what extent the dynamics of the central black holes is related to the large-scale dynamics of galaxies has yet to be clarified.[16]

From the dynamical point of view, a simple distinction can be made between rotation-supported (or cool) systems and pressure-supported (or hot) systems. Clearly, disks are the coldest systems (typical random-to-ordered kinetic energy ratios for stars or gas clouds of the thin disk in the solar vicinity are below 1 percent). However, even bulges and many low-luminosity spheroidal galaxies are to be considered cool to the extent that they have significant amounts of energy stored in the form of mean motions. In contrast, many bright ellipticals appear to be fully pressure-dominated.

When we talk about galaxies, in terms of either observations or dynamical theories, we naturally tend to refer to bright objects. Still we should keep in mind that there are many dim galaxies and that there are many unresolved problems associated with them. Much as for the luminosity distribution of stars,[17] the faint end of the luminosity distribution of galaxies is hard to determine empirically and may hide large numbers of objects. Some studies have tried to assess this distribution inside nearby clusters.[18] A commonly used distribution[19] is $f(L) \sim (L/L_\star)^\alpha \exp[-(L/L_\star)]$. The characteristic luminosity is found to correspond to an absolute magnitude $M_B^\star \approx -21$, which may reach approximately -22 if the cD galaxies are counted. The characteristic exponent is found to be $\alpha \approx -1$ for galaxies in the field and $\alpha \approx -1.25$ for cluster galaxies.[20] If a universal luminosity function indeed could be shown to underlie these data, this would be of high theoretical interest in relation to the processes of galaxy formation.[21] These considerations become especially important when we consider the distribution of galaxies at large distances and how this distribution may be affected by evolutionary processes (among which are galaxy-galaxy encounters and merging).

In this and the following three chapters the stage is set, within the proper empirical context, for a number of important dynamical issues that will be introduced starting with Chapter 5. There is clearly no intention here to provide an exhaustive discussion of the many studies that define galactic and extragalactic astronomy. For a thorough introduction to the subject, the reader is referred to monographs and review articles.[22]

Notes

1. Feynman, R. P., Leighton, R. B., Sands, M. 1963. *The Feynman Lectures on Physics*, Addison-Wesley, Reading, MA.

2. Hubble, E. 1925. *Astrophys. J.*, **62**, 409. A thorough account of the discovery made by Hubble and of the debate on the nature of the nebulae is given by A. Sandage (1961) in the introduction to his *Hubble Atlas of Galaxies*, Publ. 618, Carnegie Institution of Washington, Washington, DC.
3. We recall that the matrix mechanics and wave mechanics that are generally associated with the foundation of quantum mechanics start with Heisenberg, W. 1925. *Z. Phys.*, **33**, 879; and Schrödinger, E. 1925. *Ann. Phys.*, **79**, 361.
4. Jeans, J. H. 1915. *Mon. Not. Roy. Astron. Soc.*, **76**, 70.
5. One major catalog of galaxies is the RC3 catalog: de Vaucouleurs, G., de Vaucouleurs, A., et al. 1991. *Third Reference Catalogue of Bright Galaxies*, Springer-Verlag, New York.
6. Relatively normal galaxies have been found at redshifts larger than unity. The Hubble Deep Fields, obtained from the *Space Telescope* by observing nearly continuously for periods of ≈ 10 days in one dark spot in the constellation of Ursa Major and, later, in a region of Tucana, are populated with thousands galaxies, many of them at redshifts larger than unity; Williams, R. E., Blacker, B., et al. 1996. *Astron. J.*, **112**, 1335; Williams, R. E., Baum, S., et al. 2000. *Astron. J.*, **120**, 2735. The following Hubble Ultra Deep Field, obtained from the *Space Telescope* with a 1-million-second-long exposure in the direction of Fornax, taken at the end of 2003 and the beginning of 2004, is so far the deepest visible-light view of the cosmos, with nearly 10,000 galaxies imaged; Beckwith, S. V. W., Stiavelli, M., et al. 2006. *Astron. J.*, **132**, 1729.
7. Ashman, K., Zepf, S. E. 1998. *Globular Cluster Systems*, Cambridge University Press, Cambridge, UK.
8. Hodge, P. 1992. *The Andromeda Galaxy*, Kluwer, Dordrecht, The Netherlands.
9. Bok, B. J., Bok, P. F. 1974. *The Milky Way*, 4th ed., Harvard University Press, Cambridge, MA.
10. Setting the exact value of the distance to M87 and the Virgo cluster is important in order to calibrate the distance scale in cosmology; lower values of the distance are generally favored by studies that suggest a relatively high value for the Hubble constant. See, e.g., Tammann, G. A., Sandage, A., Reindl, B. 2008. *Astron. Astrophys. Rev.*, **15**, 289; Freedman, W. L., Madore, B. F. 2010. *Annu. Rev. Astron. Astrophys.*, **48**, 673.
11. See Schneider, P., Ehlers, J., Falco, E. E. 1992. *Gravitational Lenses*, Springer-Verlag, Heidelberg.
12. Rosati, P., Borgani, S., Norman, C. 2002. *Annu. Rev. Astron. Astrophys.*, **40**, 539.
13. Schindler, S., Hattori, M., et al. 1997. *Astron. Astrophys.*, **317**, 646; the cluster is at redshift $z = 0.45$.
14. For the initial stages of these studies, see Crane, P., Stiavelli, M., et al. 1993. *Astron. J.*, **106**, 1371; Stiavelli, M., Møller, P., Zeilinger, W. W. 1993. *Astron. Astrophys.*, **277**, 421; Harms, R. J., Ford, H. C., et al. 1994. *Astrophys. J. Lett.*, **435**, L35; Miyoshi, M., Moran, J., et al. 1995. *Nature*, **373**, 127; Eckart, A., Genzel, R. 1997. *Mon. Not. Roy. Astron. Soc.*, **284**, 576; Marconi, A., Axon, D. J., et al. 1997. *Mon. Not. Roy. Astron. Soc.*, **289**, L21; van der Marel, R. P., de Zeeuw, P. T., et al. 1997. *Nature*, **385**, 610; van der Marel, R. P., de Zeeuw, P. T., Rix, H.-W. 1997. *Astrophys. J.*, **488**, 119; Kormendy, J., Bender, R., et al. 1997. *Astrophys. J. Lett.*, **482**, L139.
15. Schödel, R., Ott, T., et al. 2002. *Nature*, **419**, 694; Gillessen, S., Eisenhauer, F., et al. 2009. *Astrophys. J.*, **692**, 1075; Genzel, R., Eisenhauer, F., Gillessen, S. 2010. *Rev. Mod. Phys.*, **82**, 3121.
16. See Ciotti, L. 2009. *La Rivista del Nuovo Cimento*, **32**, 1, and references therein.
17. But see Gould, A., Bahcall, J. N., Flynn, C. 1997. *Astrophys. J.*, **482**, 913.
18. For the Virgo cluster, Sandage, A., Binggeli, B., Tammann, G. A. 1985. *Astron. J.*, **90**, 1759, go down to the faint end of $M_B \approx -14$ (total absolute luminosity in the B band). For the Ursa Major cluster, see Verheijen, M. A. W. 1997. Ph.D. thesis, University of Groningen, The Netherlands.
19. Schechter, P. 1976. *Astrophys. J.*, **203**, 297.
20. See Binggeli, B., Sandage, A., Tammann, G. A. 1988. *Annu. Rev. Astron. Astrophys.*, **26**, 509; see also Dressler, A. 1978. *Astrophys. J.*, **223**, 765; Lugger, P. 1986. *Astrophys. J.*, **303**, 535.
21. Zwicky, F. 1942. *Phys. Rev.*, **61**, 489; 1957. *Morphological Astronomy*, Springer-Verlag, Berlin; Press, W. H., Schechter, P. 1974. *Astrophys. J.*, **187**, 425.
22. See Mihalas, D., Binney, J. J. 1981. *Galactic Astronomy*, Freeman, San Francisco; Binney, J., Merrifield, M. 1998. *Galactic Astronomy*, Princeton University Press, Princeton, NJ. For a review of the general properties of normal galaxies along the Hubble sequence, see Roberts, M. S., Haynes, M. P. 1994. *Annu. Rev. Astron. Astrophys.*, **32**, 115.

2 Observational Windows

When we make observations, we rely on a number of spectral windows for which we have instruments to study the radiation that reaches the Earth. Obviously, astronomy is centered around optical radiation. After a long period of work with photographic techniques, most of the current optical studies are based on charge-coupled-device (CCD) detectors, which are solid-state devices based on two-dimensional arrays of detection elements with a wide range of capabilities.[1] The visible light extends from the ultraviolet (UV) region (UV radiation is associated with wavelengths[2] in the range 100 to 4,000 Å) to the near-infrared (near-IR) region (IR radiation has wavelengths between 7,500 Å and the millimeter range). Observations from the ground are limited by the way the light is transmitted by the atmosphere. For example, much of the near-IR radiation is absorbed by the atmosphere, and observations beyond 1 μm are best performed at high altitude (where significant transmission occurs in correspondence with the standard IR filters J, H, and K) or directly from space.

New observational windows have been opened, especially in the second part of past century, and these have dramatically changed our view of the Universe (Fig. 2.1). A major step forward has been identification of the 21-cm line (at a frequency of 1,420 MHz; a hyperfine transition in atomic hydrogen associated with the spin-flip in the electron-proton pair[3]), which has given an enormous boost to radioastronomy.[4] Studies of the kinematics of atomic hydrogen, especially those of the 1970s and the early 1980s, have provided the decisive evidence for the existence of dark matter. Radio studies have marked significant breakthroughs in extragalactic astronomy. They have also been the starting point for the discovery of multiple images by gravitational lensing[5] and have led to what is probably the best evidence to date for the existence of massive black holes at the centers of external galaxies.[6] In different contexts, the radio window has led to major discoveries, in particular, the cosmic microwave background radiation[7] and pulsars.[8]

The possibility of using telescopes from space opened the way for observational windows that have no counterpart from the ground. The X-ray Universe has thus unfolded, starting with observations from balloons and rockets in the 1960s,[9] followed by many missions, with a major impact made by the *Uhuru* satellite[10] and the *Einstein* observatory, launched in the late 1970s,[11] and later by ROSAT (*Röntgen Satellit*) in the 1990s. This led to the discovery of hot, diffuse intergalactic (intracluster) matter and to the identification of some important iron lines[12] and of the electron-positron annihilation line at 0.511 MeV. The X-ray window turned out to be very important for our understanding of normal galaxies;[13] in the past decade, great progress has been made based on X-ray telescopes of a new generation, in particular, XMM (*X-Ray Multi-Mirror Mission*) and *Chandra*. At the same time, at lower energies, the domain of UV light was explored.[14]

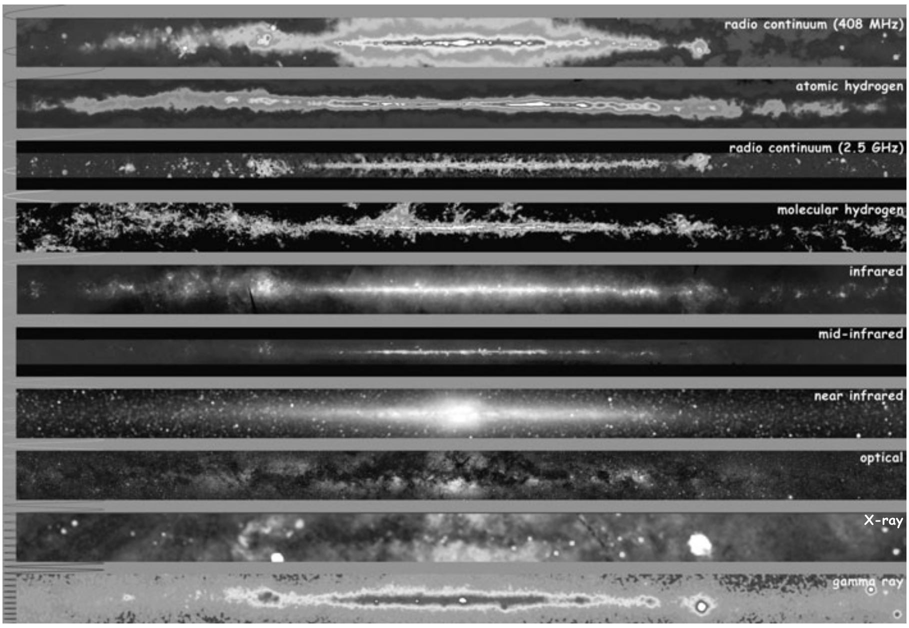

Fig. 2.1. Multiwavelength Milky Way (credit: Astrophysics Data Facility and Astronomical Data Center of the Goddard Space Flight Center, NASA). The various strips represent how the Milky Way looks within various wave bands. *From top to bottom*: Radio continuum (408 MHz), atomic hydrogen, radio continuum (2.5 GHz), molecular hydrogen (inferred from CO), IR (12–100 μm), mid-IR (6.8–10.8 μm) , near IR (1.25–3.5 μm), optical, X-ray (0.25–1.25 keV), gamma ray.

At higher energies, the *Compton Gamma Ray Observatory* had a big impact. In 1997, results from the SAX (*Satellite per Astronomia X*) satellite allowed us to pinpoint the position of the long mysterious gamma-ray bursts and thus identify them optically.[15] The study of the gamma-ray sky is now carried out by INTEGRAL (*INTERnational Gamma-Ray Astrophysics Laboratory*), *Swift* (a multiwavelength observatory dedicated to the study of gamma-ray bursts), AGILE (*Astrorivelatore Gamma a Immagini LEggero*), and *Fermi*.

IR astronomy from space [with IRAS (*Infrared Astronomical Satellite*), COBE (*Cosmic Background Explorer*), ISO (*Infrared Space Observatory*), WMAP (*Wilkinson Microwave Anisotropy Probe*), and *Spitzer*] has led to great advances in not only the cosmological context but also in new perceptions of normal galaxies;[16] the most exciting results are now coming from the data being acquired by *Herschel* and *Planck*, launched with the same rocket in 2009.

Even for the observational windows fully open from the ground, astronomy from space has led to an extraordinary set of new results. Among the many accomplishments of HST (*Hubble Space Telescope*), we should mention the discovery of Cepheid variables in the Virgo cluster of galaxies, the finding of a large number of gravitational lenses, the identification of the most distant galaxies (up to $z \approx 5$ and beyond), and the finding that many quasars are associated with relatively normal galaxies.[17] HST and the *Hipparcos* satellite have led to a much sharper determination of the relevant distance scales. Work based on HST observations of distant supernovae has led to the discovery[18] that the Universe is accelerating, leading to the current concordance