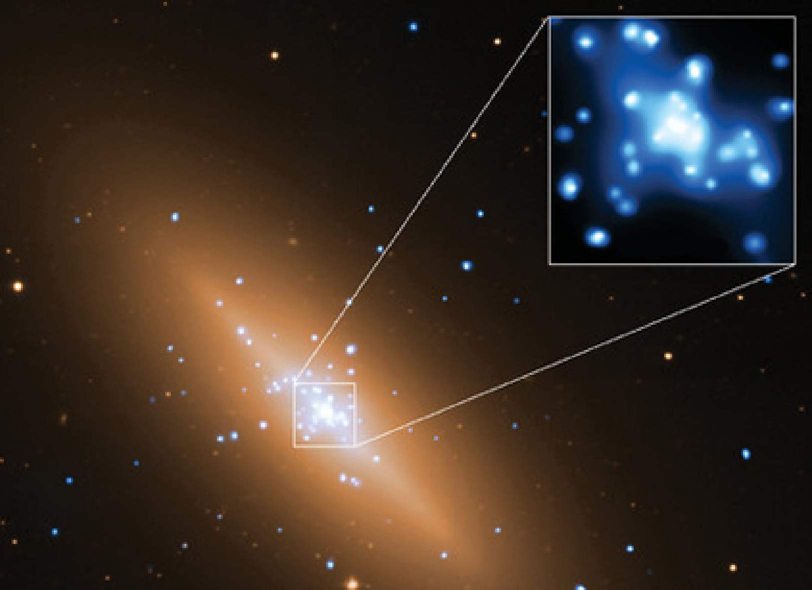

RELATIVISTIC ASTROPHYSICS OF THE TRANSIENT UNIVERSE

Gravitation, Hydrodynamics and Radiation

Maurice H. P. M. Van Putten
Amir Levinson

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In this decade, the Transient Universe will be mapped out in great detail by the emerging wide-field multiwavelength surveys, and neutrino and gravitational-wave detectors, promising to probe the astronomical and physical origin of the most extreme relativistic sources. This volume introduces the physical processes relevant to the source modeling of the Transient Universe.

Ideal for graduate students and researchers in astrophysics, this book gives a unified treatment of relativistic flows associated with compact objects, their dissipation and emission in electromagnetic, hadronic and gravitational radiation. After introducing the source classes, the authors set out various mechanisms for creating magnetohydrodynamic outflows in winds, jets and blast waves and their radiation properties. They then go on to discuss properties of accretion flows around rotating black holes and their gravitational wave emission from wave instabilities with implications for the emerging gravitational wave experiments. Graduate students and researchers can gain an understanding of data analysis for gravitational-wave data.

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To our parents

Contents

Foreword

Some of us only rarely stop to stare at the night sky, with the naked eye, let alone with binoculars or a telescope. And when we do, the heavens may seem to be majestic, peaceful, and eternal. This impression, however, is deceptive. The Universe is a magnificently violent place. Gigantic clouds contract and ignite, producing the large and fiercely burning globes that we call stars; these stars, in turn, can explode in flashes that are more luminous than millions of suns, and they can do this in a multitude of ways. Pairs of stars may coalesce, again giving rise to unimaginable outbursts of energy. Black holes may form, whose gravitational attracting force is so huge that neighboring stars, planets and gases may be accelerated to reach velocities nearing that of light, being torn apart in the process, unless they are black holes themselves.

At larger distance scales, events take place at much slower rates: galaxies devour smaller galaxies, black holes millions or even billions of times heavier than our Sun devour other objects in the central regions of galaxies. And the most catastrophic happening of all is the creation process of the Universe itself, the big bang.

Conversely, in other cosmic events, and at the smallest distance scales, atomic nuclei and subatomic particles are blown away and reach kinetic energies so enormous that no man-made laboratory, such as the Large Hadron Collider at CERN, will ever be able to match them.

Compared to all this violence, our planet Earth is amazingly peaceful and quiet. The vast emptiness of our Universe keeps us at a safe distance from all those brutal happenings; a convenient atmosphere shields us from the extremely energetic subatomic particles roaming around in space. It also moderates and filters the solar radiation. We are safe.

In fact, we can choose locations that are quiet enough to house the most sensitive scientific equipment possible to detect the minute effects of gravitational waves. These waves must originate from several of those violent outbursts described above, but because gravity is essentially an extremely weak force, gravitational waves are notoriously difficult to detect. All our technical skills and ingenuity have not yet been successful in this respect, but this may change in the near future.

Maurice H. P. M. van Putten and Amir Levinson have done a miraculous job in listing all those cosmic catastrophes taking place around us, fortunately safe distances, and they describe every possible detail of how these events can be studied and understood in a cosmic context. All of this is physics, and even though we cannot mimic any of these phenomena at full scale, we have indeed learned how to understand them just by extrapolating all those laws of nature that we have learned to describe and exploit.

Anticipating the possible detection of gravitational waves, we do the best we can to predict the expected wave forms; the more accurate templates that we can produce have the highest potential of being detected first, while establishing the *absence* of the predicted wave forms, by a statistical analysis, may equally well serve to give us further information about the Universe we live in.

The tax agency in our country once advertised with the slogan: *We can't make this more enjoyable, but we can make filling out your tax forms a lot easier for you*. Shortly after that, a mathematician entitled his inaugural lecture as follows: *I can't make it any easier for you, but certainly I can make it a lot more enjoyable*.

Van Putten and Levinson did not write an easy text, but they did make an enjoyable compilation of all those strange things that can happen in our Universe, not only providing detailed physical calculations to understand them, but also including descriptions of all the channels of radiation that we can use to receive as much information about them as we can.

Gerard 't Hooft
Institute for Theoretical Physics, Utrecht University

Preface

In this decade, we anticipate a complete window for observing the Universe with advanced multimessenger survey instruments for electromagnetic radiation, cosmic rays, neutrinos and gravitational waves.

The evolution of the Universe is largely shaped by gravity, giving rise to large scale structure in filaments and voids down to galaxies and their constituents. The associated radiative phenomena indicate an "arrow of entropy" that points to scales generally less than 1 Mpc, where we find interactive and transformative processes such as galaxy mergers, active galaxies, supernovae and gamma-ray bursts (GRBs). On these scales, the Transient Universe serves as a cosmic beacon in the era of reionization to the present. Thus, entropy appears to be increasing, from an initially low value at the birth of the Universe as conjectured by Penrose, with conceivably jumps in some of the brightest and most extreme transient events.

Multimessenger astronomy aims at the measurement of physical and astronomical parameters across various observational windows, in and beyond the electromagnetic spectrum. It promises a probe of gravity with the potential to discover the relationship between large structure formation by dark matter, galaxy formation, star formation and their end products, to unravel the astronomical origin and physical mechanism giving rise to active galactic nuclei, core-collapse supernovae (CC-SNe) and GRBs.

Ultra-high energy cosmic rays (UHECRs) and cosmological GRBs stand out as the most relativistic transient events that may be telling us about gravitation in the strongly nonlinear regime in the spacetime around black holes. Since black holes are scale free, we expect common principles at work by which supermassive and, respectively, stellar mass black holes induce high energy non-thermal emissions. High energy emissions around black holes provide signatures not only of the geometry of spacetime, but of how geometry induces novel radiation processes. The latter is widely believed to involve rotating black holes and possibly merging black hole binaries. Since gravitation is universal, we further anticipate that radiation processes induced by gravitation extend across a broad range of emission channels.

Some of the emerging multimessenger detectors offer wide-area surveys of the time-dependent Universe. They will give us a census of transient sources, their astronomical origin and host environments and, at high redshifts, their earliest cosmological manifestations. For instance, the first GRBs will track the formation of the first stars, and hence point to the first galaxies that might harbor the seeds of supermassive black holes.

The Transient Universe is observable in electromagnetic, hadronic and gravitational radiation processes. In existing curricula, these three processes are typically dispersed over a wide variety of courses in theoretical astrophysics and astronomy. Yet, observations on the Transient Universe stimulate a broader development towards a unifying picture. This book intends to provide a practical introduction along with examples of source modeling and some related data analysis techniques. These examples are directed to stimulate further innovation on multimessenger data analysis of, e.g., CC-SNe, GRBs and their associated gravitational-wave emissions.

It is advised that contemporary reviews are consulted to accompany some of our discussions. We do not claim to be complete but, rather, to provide a hands-on introduction serving those who wish to enter this exciting new field in a format suitable for a one-semester graduate course.

Much of this book developed out of research, lectures and seminars developed by the authors at the Korea Institute for Advanced Study, Tel Aviv University, DAMTP at the University of Cambridge, Osservatorio di Capodimonte (INAF-Napoli), LIGO-Caltech, Le STUDIUM IAS and LPC2E at CNRS-Orléans, the Universities of Orléans, Tours and Nanjing. In our teaching, we commonly recommend supplementary reference books on general relativity by Hawking and Ellis [275], Chandrasekhar [141], Wald [632] and 't Hooft [576], on electromagnetic radiation processes in astrophysics by Ribicki and Lightman [520] and Dermer and Menon [178], on neutrino physics in astrophysics by Giunti and Kim [244], on fluid dynamics by Chandrasekhar [140] and Batchelor [72], on compact objects by Shapiro and Teukolsky [533], and on active galaxies by Krolik [352].

We begin with an overview of transient sources and essential elements of relativistic radiation processes, hydrodynamics and magnetohydrodynamics associated with compact objects, curved spacetime and gravitational waves, blast waves, outflows and jets, some principles of thermodynamics of stellar systems and accretion disks. We apply some of these ideas to an outlook on non-thermal radiation processes around Kerr black holes.

The material presented in this book grew out of discussions with many colleagues. We wish to thank in particular Ski Antonucci, Barry Barish, Jacob Bekenstein, Roger D. Blandford, Stefano Bolognesi, Adam Burrows, E.E. Cheng Young, Edna Cheung, Massimo Della Valle, Charles D. Dermer, David Eichler, Andrew C. Fabian, Gabriele Veneziano, Alok Gupta, Chung Wook Kim, Serguei Komissarov, Kimyeong Lee, Nobuyuki Kanda, Roy Kerr, Shrinivastas Kulkarni, Fujimoto Masa-Katsu, Yuri Lyubarsky, Ehud Nakar, Changbom Park, Tom Prince, Graziano Rossi, Alessandro D.A.M. Spallicci, Erik Verlinde, Michel Tagger, Hideyuki Tagoshi, Daisuke Tatsumi, Gerard't Hooft, Kip S. Thorne, Henk van Beijeren, Eli Waxman, Piljin Yi and Fabian Ziltener for stimulating discussions, and Claire L. Poole of Cambridge University Press for her continuous attention to detail in finalizing the manuscript.

Notation

The conventional metric signature is $(-, +, +, +)$. The Minkowski metric is given by $\lceil -1, 1, 1, 1 \rfloor$.

Tensors are written in the so-called abstract index notation. Indices from the middle of the alphabet denote spatial coordinates. Four-vectors and p-forms are also indicated in small boldface. Three-vectors are indicated in capital boldface.

The epsilon tensor $\epsilon_{abcd} = \Delta_{abcd}\sqrt{-g}$ is defined in terms of the totally antisymmetric symbol Δ_{abcd} and the determinant g of the metric, where $\Delta_{0123} = 1$, which changes sign under odd permutations.

Quotation acknowledgements

Even if there is only one possible unified theory, it is just a set of rules and equations. What is it that breathes fire into the equations and makes a universe for them to describe?

Stephen W. Hawking (1942–)

Hawking, S.W., 1988, *A Brief History of Time* (New York: Bantam Dell).

It does not make any difference how beautiful your guess is. It does not make any difference how smart you are, who made the guess, or what his name is – if it disagrees with experiment it is wrong. That is all there is to it.

Richard P. Feynman (1918–1988)

From a lecture given by Feynman. With permission from Caltech and the Feynman estate.

And these little things may not seem like much but after a while they take you off on a direction where you may be a long way off from what other people have been thinking about.

Roger Penrose (1931–)

From a program transcript "Sir Roger Penrose" interviewed by Adam Spencer and aired on Australia's ABC 'Quantum' program on Thursday 6th April 2000.

In order to make further progress, particularly in the field of cosmic rays, it will be necessary to apply all our resources and apparatus simultaneously and side-by-side; an effort which has not yet been made, or at least, only to a limited extent.

Victor Francis Hess (1883–1964)

Les Prix Nobel, 1936 © The Nobel Foundation. In 1998, *Nobel Lectures in Physics 1922–1941* (Singapore: World Scientific Publishing Co.).

To this day I always insist on working out a problem from the beginning without reading up on it first, a habit that sometimes gets me into trouble but just as often helps me see things my predecessors have missed.

Robert B. Laughlin (1950–)
Les Prix Nobel, 1998 © The Nobel Foundation.
In Ekspong, G., 2002, *Nobel Lectures in Physics 1996–2000*
(Singapore: World Scientific Publishing Co.).

There are two possible outcomes: if the result confirms the hypothesis, then you've made a measurement. If the result is contrary to the hypothesis, then you've made a discovery.

Enrico Fermi (1901–1954)
Fermi, E. As quoted in Jevremovic, T., 2005,
Nuclear Principles of Engineering (New York: Springer).

Status quo, you know, is Latin for "the mess we're in."

Ronald W. Reagan (1911–2004)
With permission from the Ronald Reagan Presidential Foundation and Library.

Behind it all is surely an idea so simple, so beautiful, that when we grasp it–in a decade, a century, or a millennium–we will all say to each other, how could it have been otherwise? How could we have been so stupid?

John Archibald Wheeler (1911–2008)
Wheeler, J. A., How come the Quantum.
Annals of the New York Academy of Sciences, **480** (1986), 304–316.

Two paradoxes are better than one; they may even suggest a solution.

Edward Teller (1908–2003)
Teller, E., Teller, W., & Talley, W., 1991,
Conversations on the Dark Secrets of Physics (New York: Basic Books)

A fact is a simple statement that everyone believes. It is innocent, unless found guilty. A hypothesis is a novel suggestion that no one wants to believe. It is guilty, until found effective.

Edward Teller (1908–2003)
Teller, E., Teller, W., & Talley, W., 1991,
Conversations on the Dark Secrets of Physics (New York: Basic Books)

1

A zoo of astrophysical transient sources

Even if there is only one possible unified theory, it is just a set of rules and equations. What is it that breathes fire into the equations and makes a universe for them to describe?

Stephen W. Hawking (1942–)

The Universe as revealed in state of the art surveys appears organized with large scale clustering of galaxies in filaments bounding large scale voids, as shown in Fig. 1.1. This distribution was discovered by the Center for Astrophysics (CfA) Redshift Survey [364], and has now been mapped in great detail by the Two-Micron All Sky Survey (2MASS) [542] and the Sloan Digital Sky Survey (SDSS) [541].

The large scale structure emerged out of embryonic inhomogeneities in the early evolution of the Universe [263] as imprinted, in pattern and amplitude, in the cosmic microwave background (CMB). These fluctuations in the CMB can be seen as tiny temperature variations with an amplitude of about 10 microkelvin, roughly 10^{-5} of the average CMB temperature, 2.724 K [308]. The present day low CMB temperature results from adiabatic cooling in the cosmological expansion over 13.75 Gyr [308], since radiation decoupled from matter, when the Universe was a mere 400 kyr of age and about one thousand times smaller in linear size. By Newtonian attraction, the associated local inhomogeneities in the (dark) matter distribution gave rise to the large scale structure of the Universe, as presently observed. The evolution of this structure is accompanied by violent processes and entropy creation on scales of $\sim$1 Mpc and less [558, 263, 644], in addition to entropy of possibly cosmological origin (e.g., [238, 190]).

There is mounting evidence that many galaxies harbor supermassive black holes at their centers, with masses ranging from a few million to a few billion solar masses ($M_\odot$), and in some cases even binaries of supermassive black holes [343, 389, 157], notably the X-ray luminous binary nucleus in NGC 6240 [342] and a sample of 167 candidates based on double-peaked emission lines, associated with a circumbinary accretion disk [391]. The processes governing the formation and

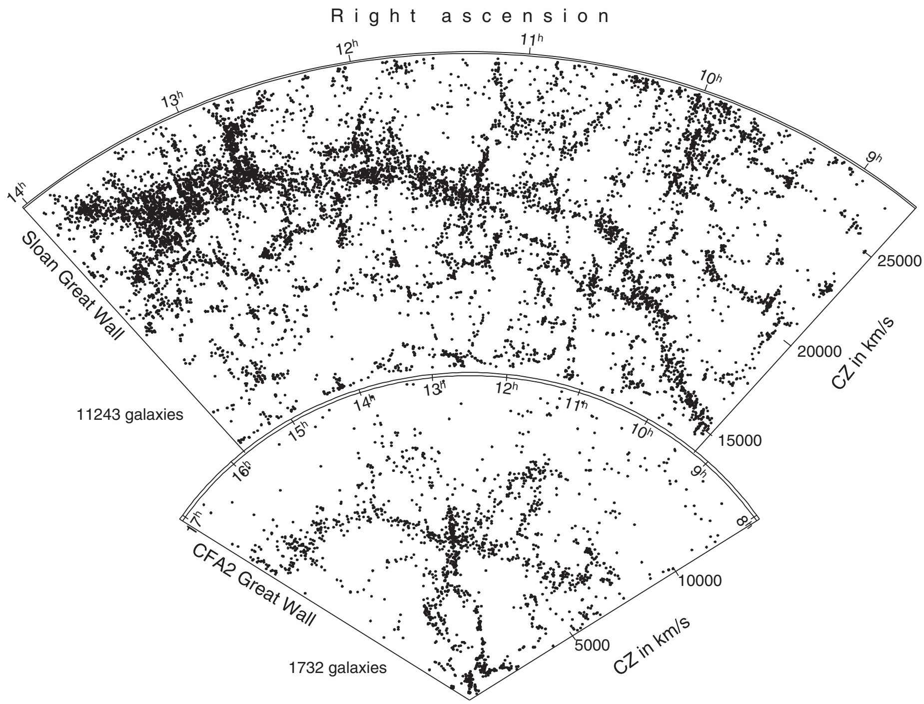

Figure 1.1 The Sloan Great Wall in the original CfA survey of the local Universe, revealing large scale structure in the distribution of galaxies, and the existence of voids. (© 1986 AAS. Reprinted with permission [364].)

evolution of these giant black holes are not well understood yet. When active, they are believed to power quasars, blazars, Seyfert galaxies, radio galaxies and other nuclear activity, as will be described in some greater detail below, and are collectively known as active galactic nuclei (AGN for short). The different types, notably BL Lacs and quasars, have distinct cosmological distributions, as shown in Fig. 1.2.

The presently best empirical evidence for the existence of supermassive black holes comes from motion of stars around the radio source SgrA* located at the center of our Milky Way Galaxy (Fig. 1.3). Long-term monitoring programs that employ high resolution near-infrared (NIR) techniques [242] have provided tight constraints on the density of the central object, ruling out alternatives to the black hole scenario. The current mass estimate of the putative black hole is $M = 4.3 \pm 0.38 \times 10^6\ M_\odot$. SgrA* is active, in featuring flares and quasi-periodic oscillations (QPOs) in remarkable similarity to the QPOs observed in some of the stellar mass accreting binaries ("microquasars," [581]) up to a scale factor set by the mass of the black hole.

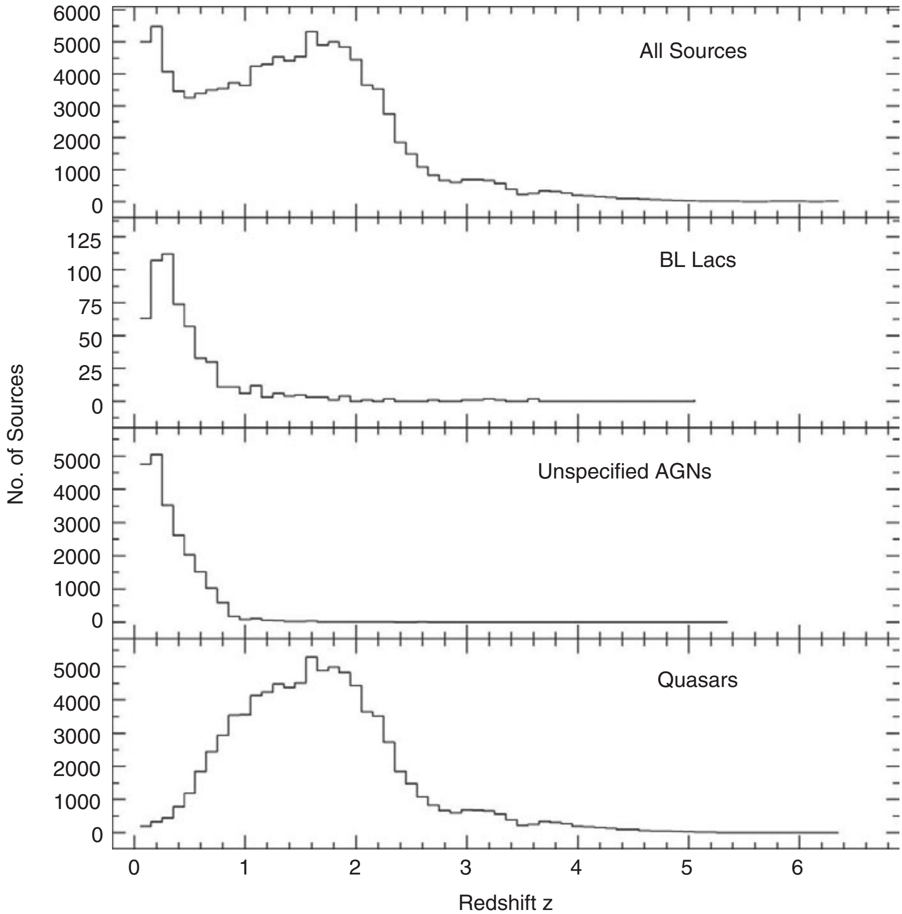

Figure 1.2 Redshift distribution of active galaxies in the VERONCAT catalog [627]. Shown are the distributions of all (*top*), BL Lac (*second*), unspecified AGN (*third*), and quasars (*bottom*); see further [527]. The last is strongly correlated to the cosmic star formation rate, probably associated with the merger history of galaxies [292] and the formation of binaries of supermassive black holes in their centers, consistent with a peak in the quasar redshift distribution around $z \simeq 1-2$ (some with double nuclei, i.e., "binary quasars" [343]).

In certain types of AGN, reverberation mapping techniques have been used to estimate the mass of the central black hole. These objects exhibit broad emission lines, thought to be emitted on sub-parsec scales by chunks of matter (clouds) that are photoinoized by the nuclear continuum source. Changes in the flux of the ionizing continuum induce changes in the luminosity of the lines emitted by the responding clouds with time delays in the observed emissions that depend on the geometry of the broad line region in the vicinity of the black hole.

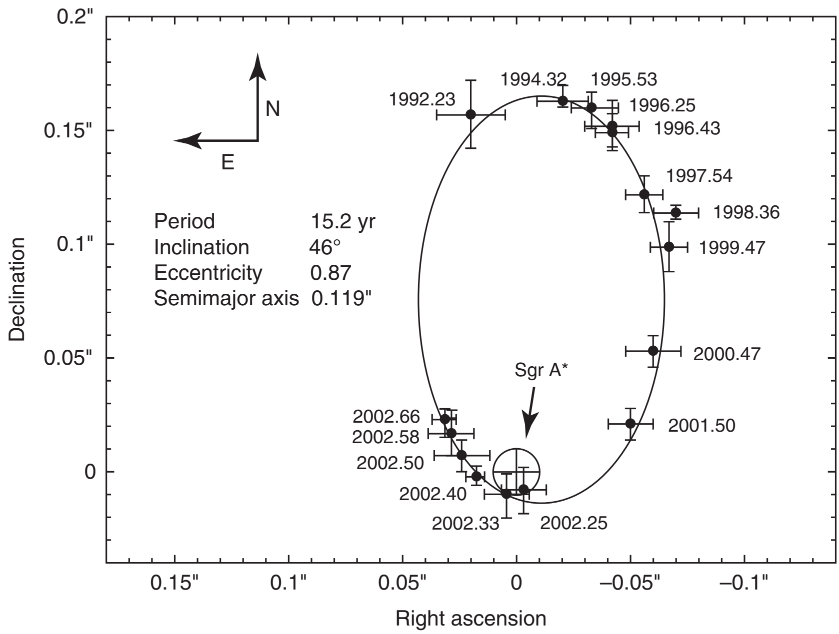

Figure 1.3 Orbit of the star S2 around SgrA*, as observed between 1992 and 2002. (© 2002 MacMillan Publishers. Reprinted with permission [529].)

Measurements of such delays in a monitored source yield an estimate for the radius of the broad line region, while the width of the lines is used to estimate the velocity of the clouds. The mass of the central object then follows upon assuming Keplerian motion of the emitting clouds. Analysis of a sample of a few dozen sources reveals a relation between the radius of the broad line region and the AGN luminosity, which can be used as a mass estimator in sources of the same type.

Dynamical estimates of black hole masses are also available for certain types of regular (inactive) galaxies. Detailed studies indicate a relation between the black hole mass M_{BH} and the velocity dispersion σ of stars in the inner regions of the galaxy, known as the $M-\sigma$ relation (Fig. 1.4). A similar relationship, between M_{BH} and the luminosity of the bulge, has also been found, albeit with a larger scatter. The mass of the black hole is about 0.1% of the mass of the host galaxy [346, 583, 208, 229]. This result suggests that the evolution of the galaxy and its nucleus are correlated. It is observationally closely related to and consistent with the Tully–Fisher [585] and the Faber–Jackson [200] relations between the luminosity and the circular velocity of stars in galaxies and, respectively, the velocity dispersion in ellipticals [518, 83, 175, 416].

The dynamical phases in the life of a galaxy involve periods of star formation and supernovae, radiation and outflows from nuclei associated with occasional

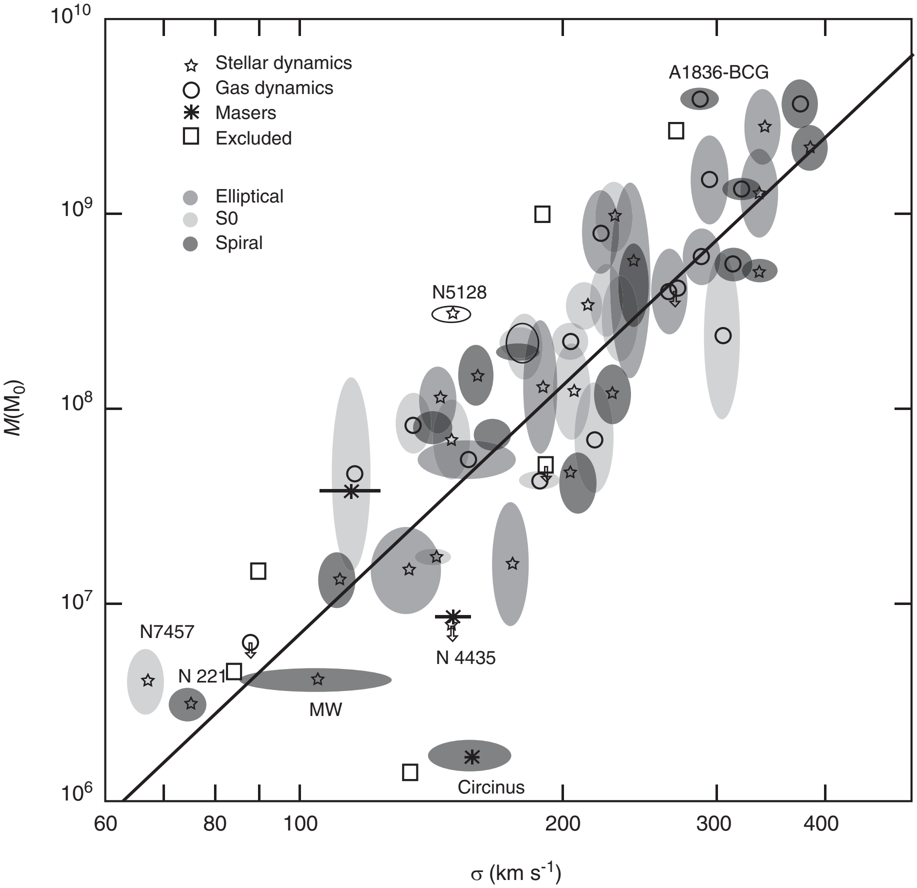

Figure 1.4 The $M-\sigma$ relation for galaxies with dynamical measurements of the black hole mass. (© 2009 AAS. Reprinted with permission [262].)

accretion of matter into the strong gravitational field of a central black hole, and stellar winds from star forming regions and supernova debris. Some of these are associated with minor and major galaxy mergers. Major mergers are important in setting the aforementioned correlation between the mass of the central black hole and the dispersion of stellar velocities [182], and effectively stimulate star formation that may reach some 30–50% of the cosmic star formation rate at its peak about a redshift of 2 (e.g., [292]).

In addition, high energy and radio astronomy reveals an abundance of transient sources in the sky related to stellar mass objects: supernovae, pulsars, soft gamma-ray repeaters (SGRs) and GRBs, with rich emission spectra on a par with the AGN. All known transient sources are associated with a host galaxy, even when, as for GRB 070125, this may be in a remote star forming region [112] or perhaps a globular cluster [619]. In fact, these transient sources all appear to be produced by compact objects representing endpoints of stellar evolution, though with different masses of their progenitor stars.

1.1 Classification of transient sources

From a physical point of view, relativistic transients may be grossly divided into those powered by accreting black holes and those powered by magnetized neutron stars. FR I and FR II radio galaxies [203], quasars, blazars, microquasars and GRBs in most scenarios are examples of systems in which the central engine involves activity around black holes; whereas in pulsars, magnetars, soft gamma-ray repeaters and gamma-ray binaries, the central engine consists of a magnetized neutron star. The basic picture, relevant to all classes of compact transients, may be represented by the general scheme:

central engine → relativistic outflow → dissipation → emission

with possibly additional emissions as yet unseen in neutrinos and gravitational waves from a central accretion disk or torus.

Despite an apparent diversity in the phenomenology of these classes of compact relativistic sources, they share much of the underlying physics even though the energy source may be distinct, i.e., in the process of accretion in the gravitational field of a black hole or the energy extraction from a magnetized, rotating neutron star.

The following chapters address the main topics involved in the above scheme, specifically, general relativity, relativistic magnetohydrodynamics (MHD), physics of shock waves and blast waves, the microphysics of radiation processes, hadronic interactions, the structure of magnetized accretion disks and multimessenger emissions around rotating black holes.

1.1.1 Blazars

Blazars are compact extragalactic radio sources characterized by rapid variability, ejection of superluminal radio knots, prodigious gamma-ray emission, and high polarization. They are members of a larger class of sources, designated as radio loud, that exhibit radio jets extending over many decades in radius [75]. An example of an extended radio source is shown in Fig. 1.5.

The rapid variability and the superluminal motion of radio knots often seen in blazars is indicative of a relativistic expansion of the emitting fluid. According to the unified model [588], both compact and extended radio sources belong to the

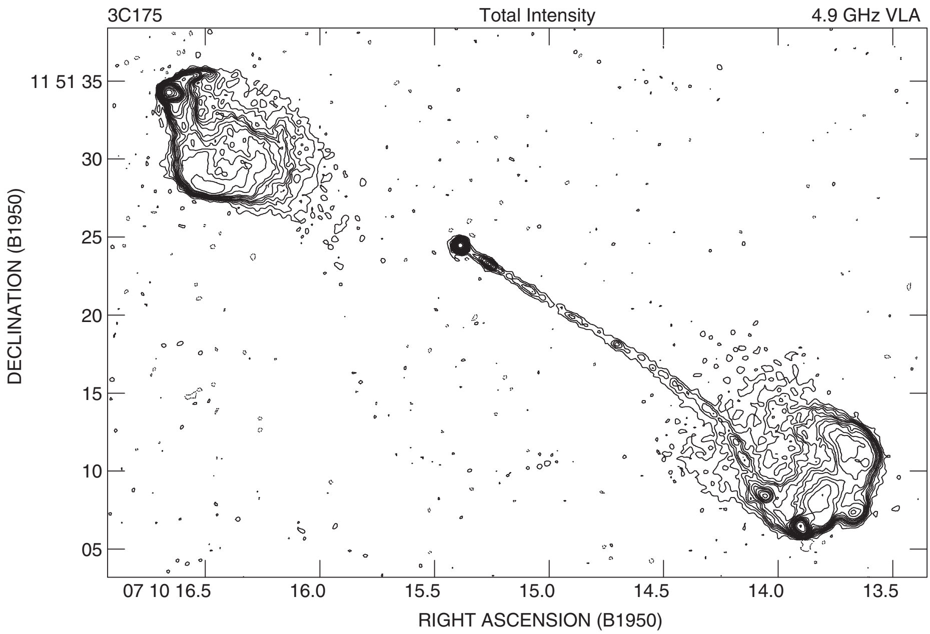

Figure 1.5 Radio (6 cm) image of 3C175 ($z = 0.768$), a radio-loud AGN with FR II morphology featuring relativistic outflows terminating in bright lobes. The apparent one-sided jet is due to relativistic beaming. (© 1994 AAS. Reprinted with permission [115].)

same class of physical objects, distinguished observationally by orientation to the observer, with jets pointing in our direction classified as blazars.

Over seven hundred blazars have been detected at energies above 100 MeV by EGRET (Energetic Gamma Ray Experimental Telescope) onboard the late Compton Gamma Ray Observatory, and by its present successor, the Fermi Observatory. Their distances and gamma-ray luminosities span a wide range, with the most powerful sources (e.g., 0528+134, 4C38.41) exhibiting isotropic equivalent gamma-ray luminosities as high as 10^{49} erg s^{-1}. Despite observational efforts, only a few extended radio sources and no radio-quiet AGN have been detected at gamma-ray energies. This apparently exclusive association of gamma-ray emitting AGN with compact radio sources strongly supports the unified model, suggesting that the gamma-rays are produced inside the jet and are beamed. Broadly, the very high energy (VHE) spectra cover 0.1–100 GeV with spectral indices α_γ between 0.7 and 1.4.

The spectral energy distribution of blazars is characterized by two main spectral components: a low energy component, peaking in the submm to UV, depending on source type, and a high energy one peaking at gamma-ray energies. A typical

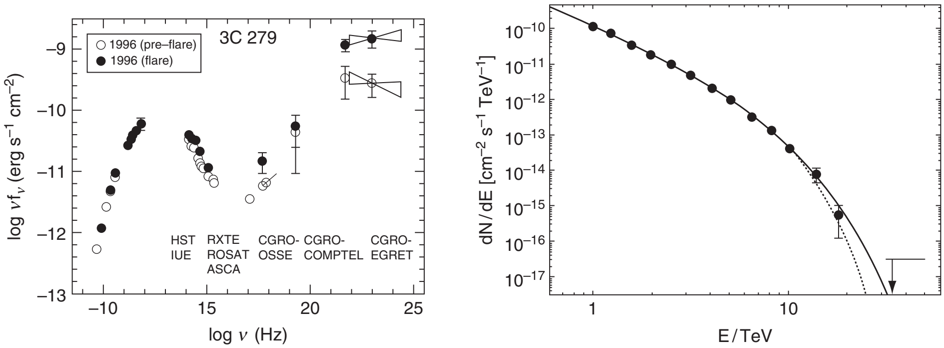

Figure 1.6 Spectral energy distribution of the blazar 3C279 in the energy range up to about 1 GeV (*left*) and the TeV spectrum of Mrk 421 (*right*). (© AAS 1995, 1997. Reprinted with permission [26, 638].)

example is shown in Fig. 1.6 (left). The beamed radio-to-UV emission is most likely synchrotron radiation by non-thermal electrons accelerated *in situ* (the synchrotron spectrum may extend up to hard X-ray energies in BL Lac objects). The origin of the high energy emission is thought to be inverse Compton scattering of synchrotron photons (sychrotron self-Compton mechanism [345]) and/or external radiation, presumably emanating from the inner parts of an accretion disk, by the same electrons. The fact that the spectrum extends well above 10 GeV in most gamma-ray AGN suggests that $e^{\pm}$ pair creation and annihilation may play an important role in shaping the spectrum. As will be discussed further below, synchrotron, inverse Compton and pair creation and annihilation are dominant radiation processes in all compact relativistic sources, not only blazars. They will be studied in detail in Chapter 2.

TeV blazars form a subclass of blazars whose spectra extend well into the TeV band. About two dozen blazars have been reported thus far as TeV sources by atmospheric Cerenkov imaging telescopes such as the High Energy Stereoscopic System (HESS) [25, 32], the Major Atmospheric Gamma Imaging Cerenkov (MAGIC) telescope [35], and the Very Energetic Radiation Imaging Telescope Array System (VERITAS) [348, 351]. The majority of TeV blazars are high-frequency-peaked BL Lac (HBL) objects located at relatively low redshifts ($z < 0.2$). The energy spectra above 100 GeV are best fitted by a power law with a cut-off around a few TeV (exceeding 10 TeV in some cases, e.g., Fig. 1.6). This is somewhat surprising, since at TeV energies strong attenuation of the flux by $\gamma\gamma$ absorption on the extragalactic background light (EBL) is expected even at modest redshifts. Quite generally, the EBL is associated with redshifted emissions from dust and stars in the range of wavelengths between 100 nm and 1 mm, constituting the dominant opacity source at TeV energies on cosmological

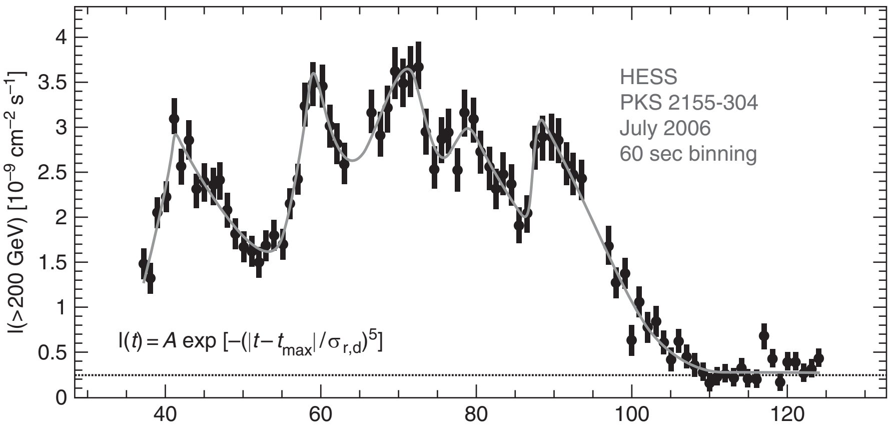

Figure 1.7 Light curve of the >200 GeV emission of PKS 2155-304 during an extreme flare. Large amplitude variations of the flux over a time scale of a few minutes are evident. Horizontal time scale is minutes. (© 2007 AAS. Reprinted with permission [30].)

scales. TeV blazars are now providing the most stringent constraint on the EBL, e.g., [501].

Strong, rapid variability over the entire electromagnetic spectrum is one of the characteristics of blazar emissions. Large amplitude variations on time scales of days to weeks are typical for many gamma-ray blazars, particularly at gamma-ray energies [333, 210]. Given the limited time resolution of the GeV detectors it is conceivable that the high energy emissions in blazars vary on even shorter time scales. Indeed, faster flux variations have been reported by the atmospheric Cerenkov experiments for some TeV blazars. In the most extreme cases, e.g., PKS 2155-304, doubling times as short as a few minutes have been measured (Fig. 1.7). As will be explained in Chapter 2, this rapid variability of the hard gamma-ray emission provides severe constraints on the bulk Lorentz factor of the outflow and on the compactness and location of the emission region. Lorentz factors in excess of 50 have been inferred for the TeV emitting fluid in the extreme TeV blazars (e.g., [378, 74]).

The short durations of extreme TeV flares also provide interesting constraints on the properties of the central engine. By causality arguments it is expected that the variability time t_{var} of any episodic event will be limited by the mass M_{BH} of the black hole, namely,

$$t_{var} \geq R_s/c, \tag{1.1}$$

for a corresponding Schwarzschild radius $R_s = 2GM_{BH}/c^2$.

The extreme flare exhibited in Fig. 1.7 implies a black hole mass $M_{BH}/M_{\odot} < 5 \times 10^7$. This value is inconsistent with the black hole/bulge relation shown in Fig. 1.4, which for PKS 2155-304 yields $M_{BH}/M_{\odot} \sim 2 \times 10^9$ [30]. Possible explanations are discussed in [380]. Furthermore, to account for the observed luminosity of the TeV flare, near-Eddington accretion rates are required, regardless of the mass of the black hole. This has interesting implications for the physics of accretion [380].

1.1.2 Microquasars and gamma-ray binaries

Microquasars are Galactic X-ray binary (XRB) systems that exhibit relativistic radio jets similar to blazars, but on stellar scales [108, 205, 283, 428] (see for example Fig. 1.8). These systems are believed to consist of a compact object – a neutron star or a black hole – and a giant stellar companion (Fig. 1.9). Mass transfer from the companion star to the compact object forms an accretion disk, and the presence of the jets makes them similar to quasars except for scale, hence their name "microquasars." The analogy may not be only morphological. It is commonly believed that the physical processes that govern the formation of the accretion disk and the ejection of plasma into the jets are similar or closely related for both systems. Galactic microquasars may therefore be considered as nearby laboratories, where models of distant and more powerful quasars can be tested. (Note, however, that the angular scales of the event horizon of supermassive black holes in powerful AGN are larger than those of the stellar mass black holes in Galactic microquasars by up to a few orders of magnitude.)

Based on this analogy, gamma-ray emission from microquasars was predicted shortly after their discovery [54, 371]. Early attempts to detect microquasars with EGRET yielded only upper limits [372]. Tentative identifications of two EGRET sources with the high mass X-ray binaries (HMXBs) LS I+61 303 [334] and LS 5009 [465] were subsequently reported, and confirmed later by TeV observatories [27, 34]. It has also been proposed that microquasars may be potential sources of VHE neutrinos for the upcoming cubic-kilometers neutrino detectors [374]. Both photomeson interactions at the base of the jet [374] and nuclear collisions in a dense stellar wind [154] have been considered.

There are, nonetheless, some important environmental differences that can affect the resulting high energy emissions from the system. In particular, in microquasars associated with a high mass stellar companion (HMXBs), the hydrodynamics and emission from the jet may be subject to, or dominated by, interactions with the wind and radiation from the stellar companion. A clear signature of such interactions has been observed in the TeV flux from two microquasars, LS 5039 and LS I+61. In both systems, significant modulation of the TeV flux on orbital time scale has been

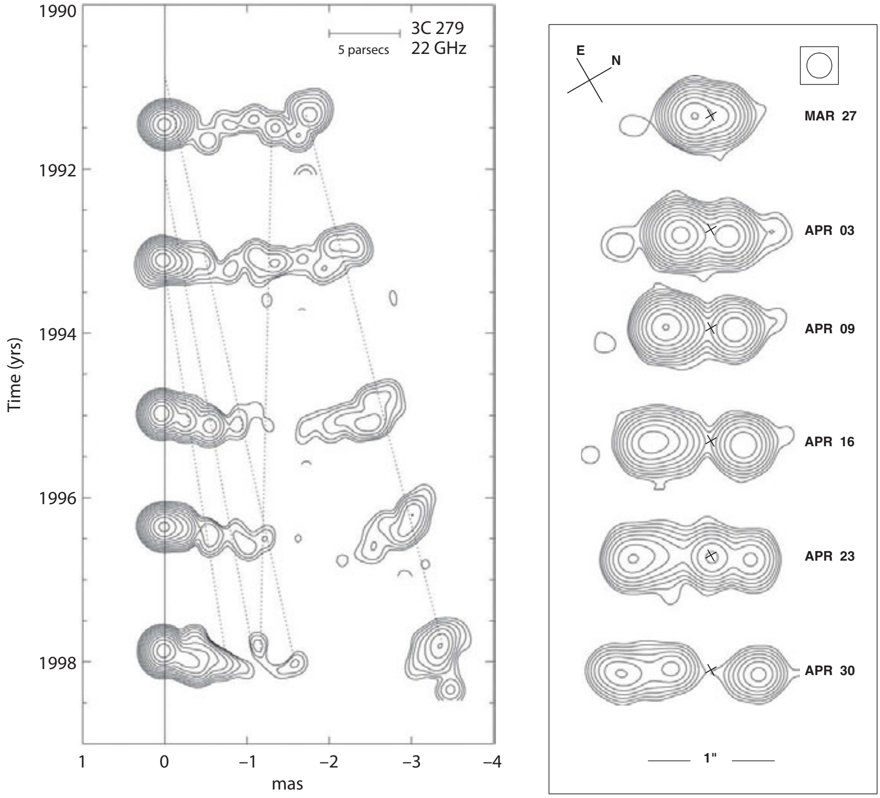

Figure 1.8 (*Left*) A sequence of radio (22 GHz) maps of the (extragalactic) blazar 3C279 at a redshift $z = 0.536$, displaying the position of the core (*solid line*) and the trajectories of various brightness features (ejecta, *dashed lines*) with apparent superluminal motions ranging from $4.8c$ to $7.5\,c$. (Image courtesy of NRAO/AUI. © 2001 AAS. Reprinted with permission [639].) (*Right*) A sequence of observations of the (galactic) microquasar GRS 1915+105 (*crosses*) shows a strikingly similar morphologic behavior on vastly smaller time and angular scales, displaying ejecta with apparent velocities of $1.25 \pm 0.15\,c$ and $0.65 \pm 0.08\,c$ corresponding to a proper motion of about $0.92 \pm 0.08\,c$ at an angle of $70 \pm 2°$ to the line-of-sight. (© 1994 MacMillan Publishers. Reprinted with permission [428].)

detected by HESS, as indicated in Fig. 1.10. Recent observations of both objects by Fermi, formerly GLAST (Gamma-ray Large Area Space Telescope) [13, 12] reveal similar modulations at GeV energies, albeit at different orbital phases. A comparison of the GeV and TeV data in Fig. 1.11 clearly indicates two components, one that peaks at a few GeV and a second one extending to TeV energies. This, and the phase difference between the two components, suggests either a different origin or opacity effects.

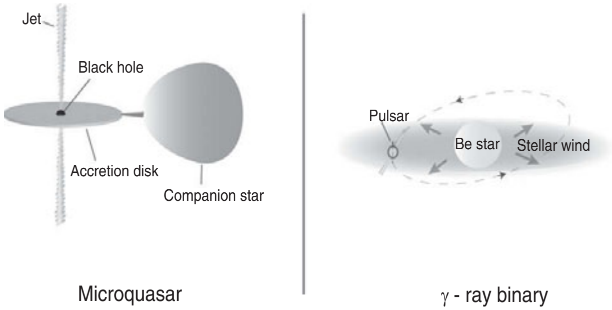

Figure 1.9 Schematic illustration of a microquasar (*left*) and a gamma-ray binary (*right*).

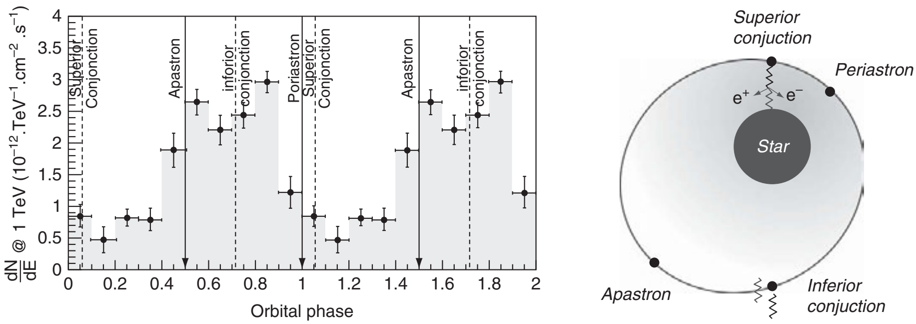

Figure 1.10 Photon count as a function of orbital phase in LS 5039 (*left*). The flux peaks near inferior conjunction (as illustrated in the *right* panel) suggest that the modulation may be due to a change in pair-production opacity. (Reprinted with permissions from HESS.)

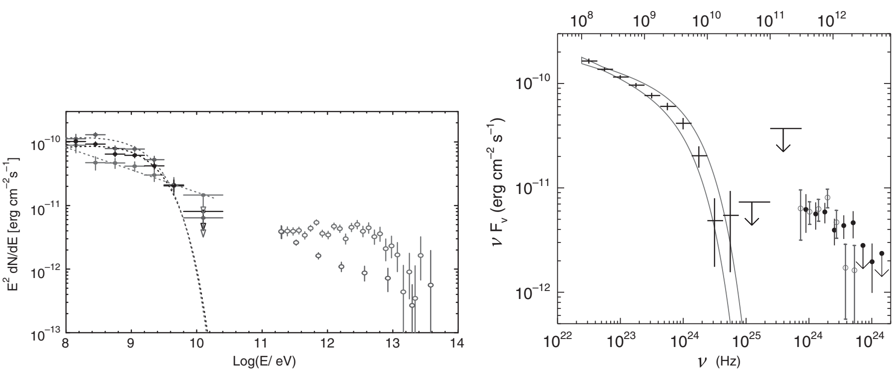

Figure 1.11 The gamma-ray spectra in the range of 100 MeV to >10 TeV of LS 5039 (*left*) and LS I+61 303 (*right*). (© 2009 AAS. Reprinted with permission [12, 13].)

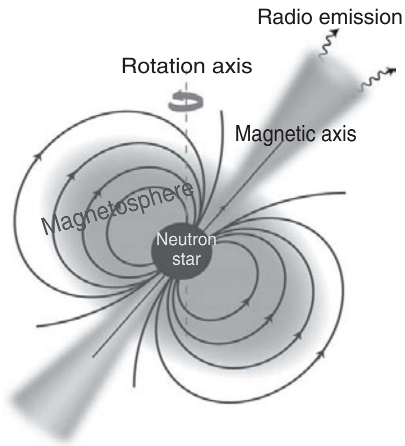

Figure 1.12 Schematic illustration of a pulsar with an offset between its rotation axis and magnetic axis, where the latter provides a channel for non-thermal emissions from radio to gamma-ray wavelengths. Spin down of the neutron star is due to shedding of angular momentum via all open magnetic field lines.

The nature of the compact object in LS 5039 and LS I+61 303 is controversial [108]. It could well be that these systems are powered by a pulsar rather than an accreting black hole, in what is now termed a gamma-ray binary [188]. In such a scenario, the interaction of the pulsar wind with the dense wind expelled by the companion star produces a pulsar wind nebula with properties that may vary with orbital phase (see the right panel in Fig. 1.9 for illustration). A prototypical example of such a system is PSR B1259-63.

The temporal behavior of microquasars appears to be rather complex. They exhibit large amplitude variations over a broad range of time scales and frequencies, with apparent connections between the radio, IR, and soft/hard X-ray fluxes [273, 652]. The characteristics of the multiwaveband behavior depend on the state of the source, that is, whether the source is in a very high, soft/high or low/hard state. The ejection of radio jets occurs typically during low/hard states, providing important information on a connection between accretion and jet formation.

1.1.3 Pulsars and magnetars

Pulsars are rapidly spinning and highly magnetized neutron stars that emit beams of particles and electromagnetic radiation along a magnetic axis. The observed pulsations are due to misalignment of the magnetic axis and the rotation axis, as in a "lighthouse" effect (Fig. 1.12). Over 1500 radio pulsars have been detected since their discovery in 1967 by Bell and Hewish [282], with rotation periods P

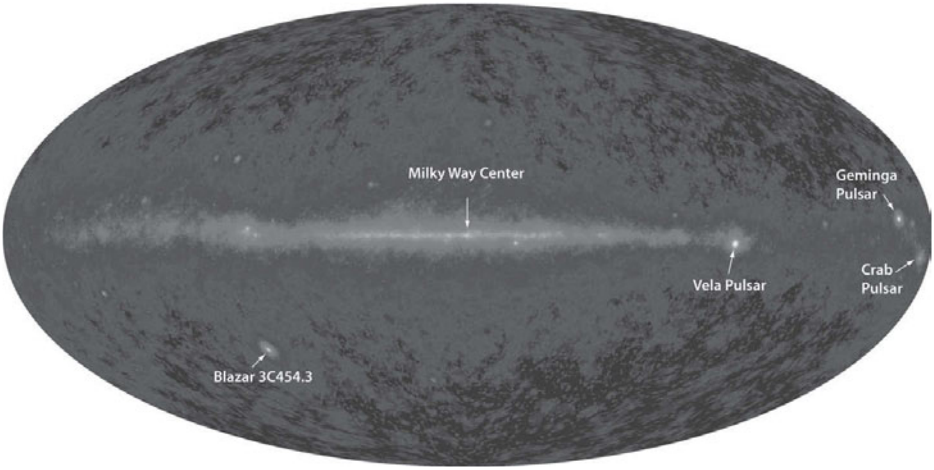

Figure 1.13 The all-sky Fermi survey including the location of gamma-ray emitting pulsars (*circles*). Less than one-third of the background gamma-rays can be attributed to AGN [18, 19]. (Courtesy of NASA/DOE/International LAT Team of the Fermi mission.)

ranging from a few milliseconds to a few seconds. The brightness temperatures inferred from the observed radio luminosities and source size are enormous, implying coherent emission. This radio emission makes up only a tiny fraction of the spin down energy – the power source of the pulsar. A significant fraction of the spin down power is radiated at X-ray and gamma-ray energies, as indicated by the first Fermi LAT Catalog of Gamma-ray Pulsars [15] (Fig. 1.13). Many of the gamma-ray pulsars are radio quiet and in others the high energy emission is not in phase with the radio emission, suggesting that this component originates from a different location in the magnetosphere. Pulsars hence exemplify the need for multi-wavelength observations to perform true calorimetry on the energy reservoir, here in the form of the spin energy of the rotating neutron star.

The rotation of the pulsar produces strong electric fields that extract electric charges from the neutron star surface, forming a magnetosphere filled with a dilute plasma. Particles produced on open magnetic field lines are accelerated by the strong electric fields near the stellar surface, giving rise to a relativistic polar outflow to infinity. The radio emission is produced by this ultra-relativistic plasma beam in the polar cap through some coherent emission mechanism that is not well understood at present. The total power emitted slows down the pulsar rotation over time to a threshold spin period below which the radio emission mechanism turns off. This critical spin period depends on the surface magnetic field strength, and it defines the end of an active pulsar phase of about $10^7 - 10^8$ years. The relation between the critical spin period and the surface magnetic field (or alternatively