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Maurice H. P. M. Van Putten and Amir Levinson
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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

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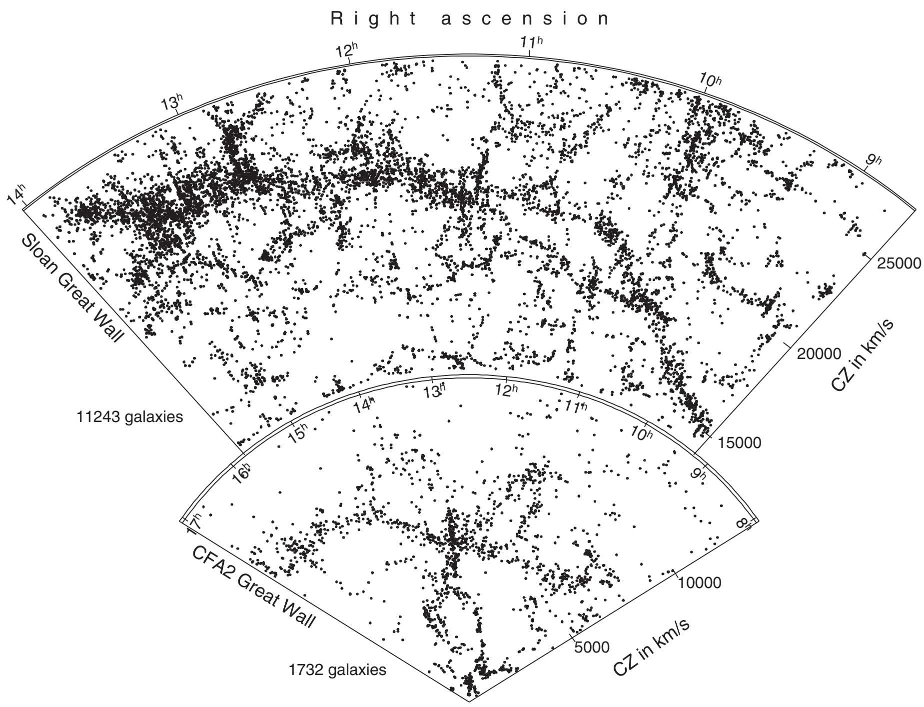

Figure 1.1 The Sloan Great Wall in the original CfA survey of the local Universe, revealing large scale structure in the distribution of galaxies, and the existence of voids. (© 1986 AAS. Reprinted with permission [364].)

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.

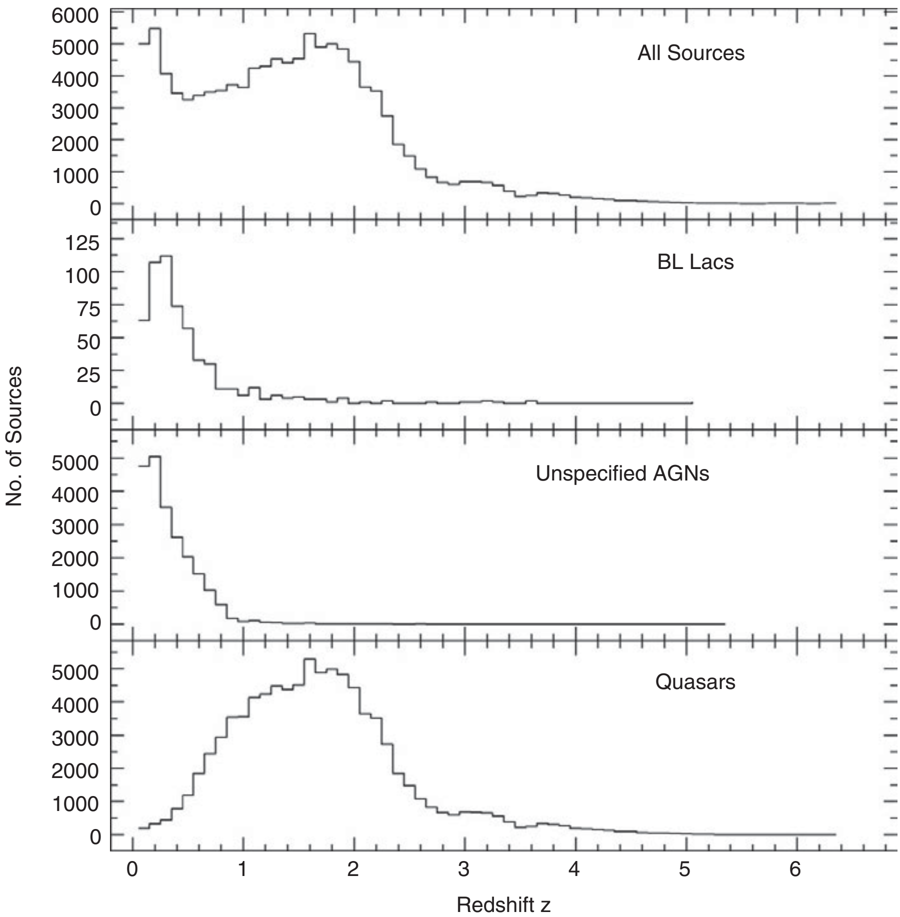

Figure 1.2 Redshift distribution of active galaxies in the VERONCAT catalog [627]. Shown are the distributions of all (*top*), BL Lac (*second*), unspecified AGN (*third*), and quasars (*bottom*); see further [527]. The last is strongly correlated to the cosmic star formation rate, probably associated 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.

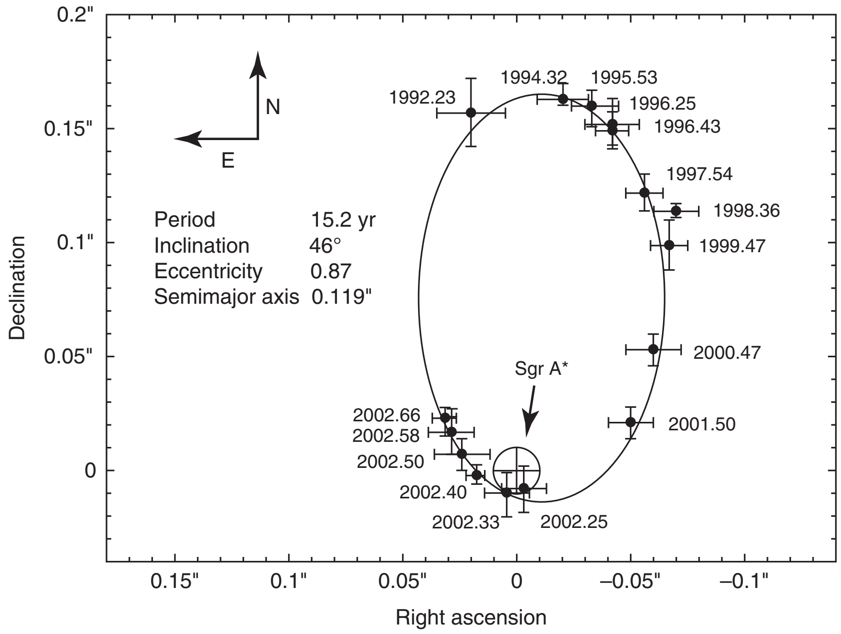

Figure 1.3 Orbit of the star S2 around SgrA*, as observed between 1992 and 2002. (© 2002 MacMillan Publishers. Reprinted with permission [529].)

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

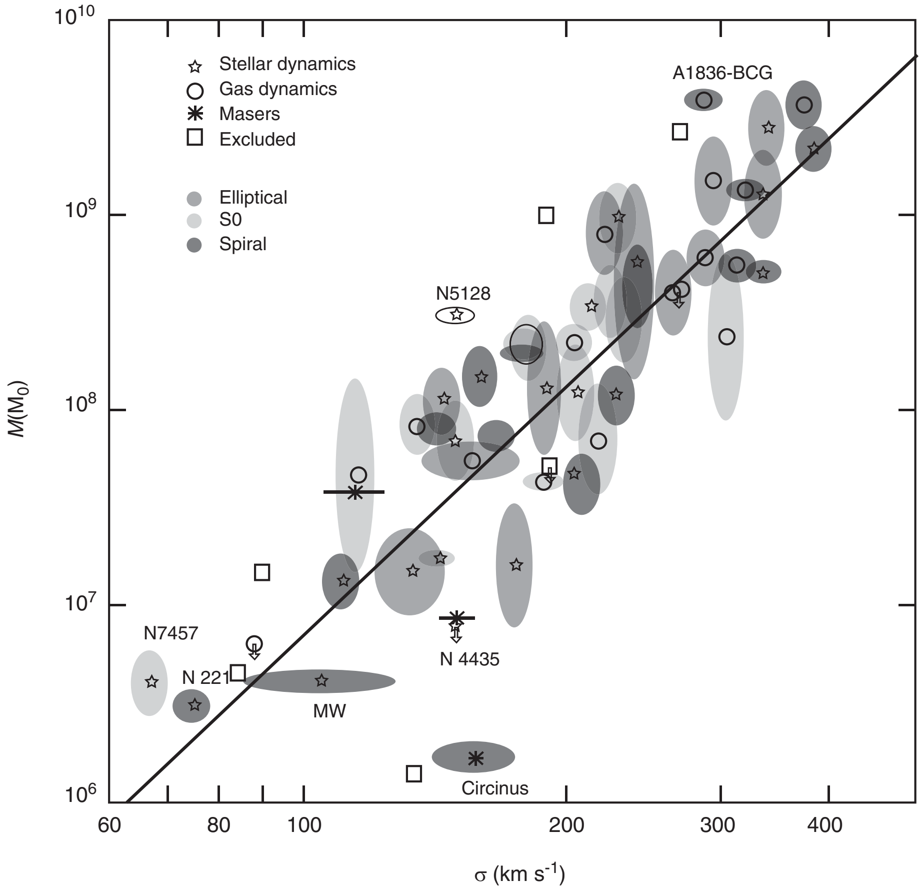

Figure 1.4 The $M-\sigma$ relation for galaxies with dynamical measurements of the black hole mass. (© 2009 AAS. Reprinted with permission [262].)

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

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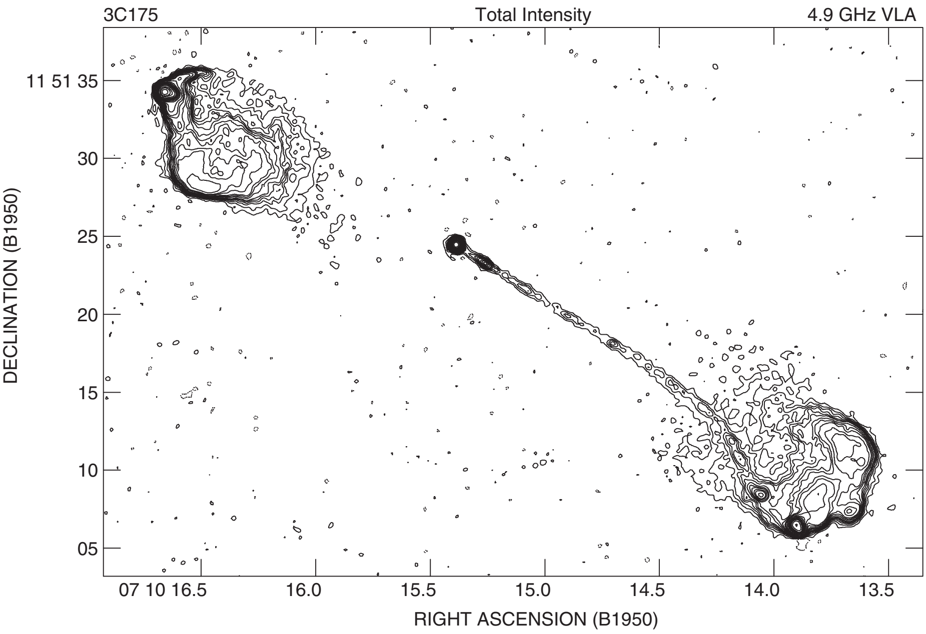

Figure 1.5 Radio (6 cm) image of 3C175 ($z = 0.768$), a radio-loud AGN with FR II morphology featuring relativistic outflows terminating in bright lobes. The apparent one-sided jet is due to relativistic beaming. (© 1994 AAS. Reprinted with permission [115].)

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

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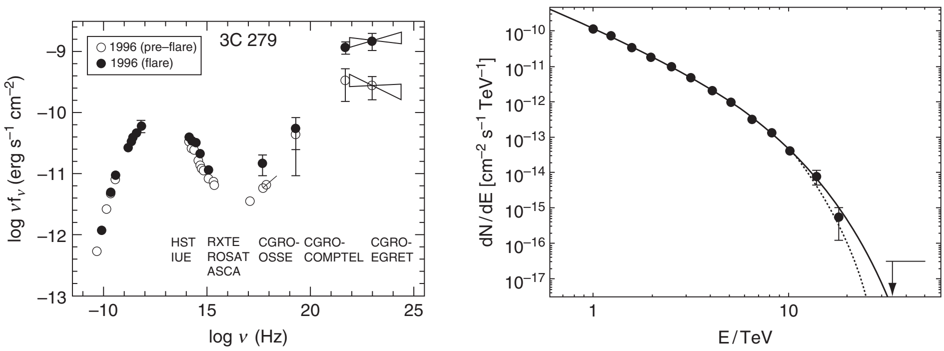

Figure 1.6 Spectral energy distribution of the blazar 3C279 in the energy range up to about 1 GeV (*left*) and the TeV spectrum of Mrk 421 (*right*). (© AAS 1995, 1997. Reprinted with permission [26, 638].)

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

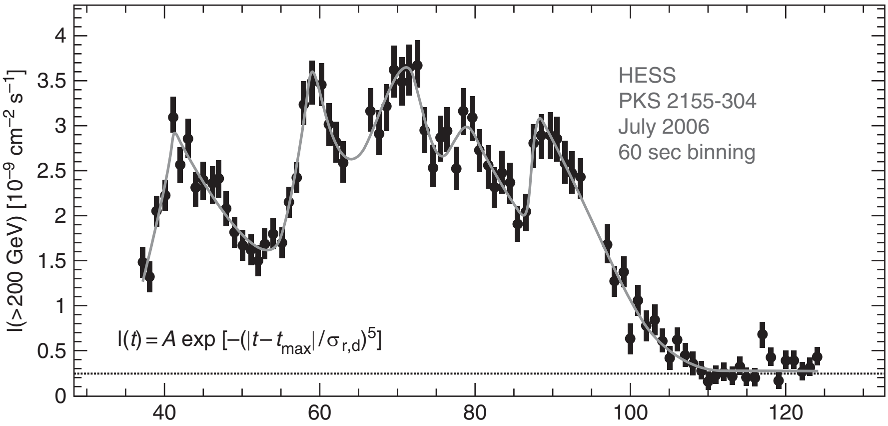

Figure 1.7 Light curve of the >200 GeV emission of PKS 2155-304 during an extreme flare. Large amplitude variations of the flux over a time scale of a few minutes are evident. Horizontal time scale is minutes. (© 2007 AAS. Reprinted with permission [30].)

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 Schwarzchild 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