High Energy Astrophysics in Context

1 Some references

The following set of volumes is an outstanding summary of the field of High Energy Astrophysics and its relation to the rest of Astrophysics

High Energy Astrophysics, Vols. 1,2 and 3. M.S. Longair, Cambridge University Press

The following book is a good account of various emission processes in Astrophysics. Some details are left out and these are provided in these notes.

Radiative Processes in Astrophysics, G. Rybicki and A.P. Lightman

The following books contain excellent accounts from differing perspectives of the Physics of AGN

An Introduction to Active Galactic Nuclei, B.M. Peterson

Active Galactic Nuclei, J.H. Krolik, Princeton Series in Astrophysics

Active Galactic Nuclei, I. Robson, Wiley-Praxis Series in Astronomy and Astrophysics

2 What is High Energy Astrophysics?

Defining features:

1. Astrophysical phenomena that involve particles of "high energy".
2. Frequently this refers to photons. X-ray and gamma-ray astronomy are considered parts of high energy astrophysics
3. High energy, relativistic electrons are also responsible for low energy emission in the form of radio waves. Aspects of radio astronomy are also considered to be part of HEA
4. The above concentrates on the physics of emission. Frequently the environments in which this emission occurs are created by

the transfer of prodigious amounts of energy and momentum. e.g.

- Accretion onto black holes
- Transfer of energy and momentum via jets
- Processing of the interstellar medium via blast waves whose ultimate source of energy is prodigious e.g. the explosion of a star
- Heating of the interstellar medium of a galaxy by winds and supernovae

The origins of HEA

(See Longair, Vol. 1 for a comprehensive account).

1. Direct measurement of the energy and composition of cosmic

rays.

2.Interplanetary physics - fast particles in the interplanetary medium; acceleration of fast particles at the Earth's bow shock.

3.Solar physics – solar radio bursts, solar flares.

4. Study of the radio emission from the Interstellar Medium (related to cosmic rays).

5.Radio emission from radio galaxies and quasars.

Relatively new areas of HEA

1. X-ray astronomy.

- The intracluster medium.
- Atmospheres of elliptical galaxies.
- X-ray emission from the solar corona and the atmospheres of

other stars.
- Accretion onto neutron stars and black holes.
- The coronae of black hole accretion discs.
- X-ray synchrotron emission from jets near black holes.

2. Gamma-ray astronomy.

- GeV and TeV emission from blazars.
- GeV emission from the Galaxy.
- GeV and TeV emission from supernova remnants.

3 The tools of HEA

1. A good understanding of the radiation field, including polarisation.

2. The physics of emission processes:

- Thermal emission from a plasma
- Nonthermal processes from high energy particles e.g. synchrotron and inverse Compton emission
- The propagation of radiation e.g. Faraday rotation of a linearly polarised wave

3. Mass, momentum and energy transport in high energy environments:

4.Special and general relativity

5.Astrophysical fluid dynamics

4 Units

Often in high energy astrophysics, energies, frequencies, temperatures are expressed in electron volts (eV), where

$$1\ \text{eV} = \text{Energy gained by an electron in a potential drop of 1 volt}$$

$$= 1.60\times10^{-19}\ \text{C}\times 1\ \text{V} = 1.60\times10^{-19}\ \text{J}$$

Frequency -> Energy

$$E = h\nu \Rightarrow E(\text{eV}) = 4.136\times10^{-15}\left[\frac{\nu}{\text{Hz}}\right]$$

so that a typical X-ray energy of 1 keV corresponds to $\nu = 2.4\times10^{17}$ Hz.

Temperature -> Energy

$$E = kT \Rightarrow E(\mathrm{eV}) = 8.617\times10^{-5}T$$

so that, again, an energy of 1 keV corresponds to a temperature of

$T = 1.160\times10^{7}\,°\mathrm{K}$.

5 The blackbody spectrum

5.1 Specific intensity

A number of the emission processes that are important in high energy astrophysics are nonthermal, e.g. synchrotron emission, inverse Compton emission, relativistic bremsstrahlung, i.e. the emission arises from processes in which the matter and radiation

are *not* in thermal equilibrium. It is important and useful to compare these spectra to the spectrum which arises when matter and radiation are in equilibrium, the blackbody spectrum in which the specific intensity (brightness)

$$B_\nu(T) = \frac{2h\nu^3}{c^2}\left[e^{\frac{h\nu}{kT}} - 1\right]^{-1}$$

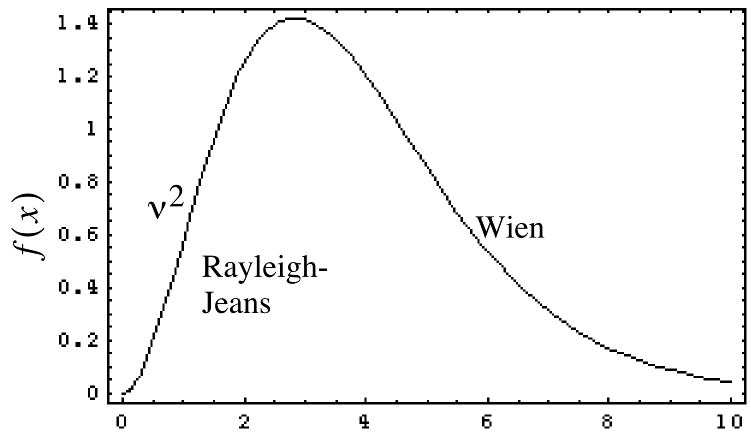
We may write this function as:

$$B_\nu(T) = \left[\frac{2k^3T^3}{c^2h^2}\right]x^3[e^x - 1]^{-1} \qquad x = \frac{h\nu}{kT}$$

The plot of the function

$$f(x) = x^3[e^x - 1]^{-1}$$

is given in the following diagram.



$$x = \frac{h\nu}{kT}$$

5.2 Limits

Rayleigh-Jeans limit

$$\frac{h\nu}{kT} \ll 1 \qquad f(x) \to x^2 \qquad B_\nu(T) \to \frac{2kT}{c^2}\nu^2$$

so that the slope on a log-log plot (see above) is +2.

This is a limit often encountered in radio astronomy. Also, even when a spectrum is manifestly *not* a blackbody spectrum, the equation

$$I_\nu = \frac{2kT_b}{c^2}\nu^2$$

is used to define a brightness temperature, T_b.

Wien limit

When $\frac{h\nu}{kT} \gg 1$,

$$B_\nu(T) \sim \frac{2h\nu^3}{c^2}\exp\left[-\frac{h\nu}{kT}\right]$$

and the spectrum has an exponentially vanishing tail.

The blackbody spectrum peaks at $\frac{h\nu}{kT} \cong 2.82144$ so that the peak can be used to estimate the temperature.

5.3 Energy density

The energy density per unit frequency is given in terms of the mean intensity, J_ν, by

$$u_\nu = \frac{4\pi}{c}J_\nu \qquad J_\nu = \frac{1}{4\pi}\int_{4\pi} B_\nu d\Omega$$

The total energy density is:

$$\begin{aligned}\varepsilon_{rad} &= \int_0^\infty u_\nu d\nu = \frac{4\pi}{c}\int_0^\infty B_\nu(T)d\nu \\ &= \frac{8\pi h}{c^3}\int_0^\infty \frac{\nu^3}{\left[\exp\left(\frac{h\nu}{kt}\right) - 1\right]}d\nu \\ &= \frac{8\pi k^4 T^4}{h^3 c^3}\int_0^\infty \frac{(h\nu/kt)^3}{\left[\exp\left(\frac{h\nu}{kt}\right) - 1\right]}d\left(\frac{h\nu}{kt}\right)\end{aligned}$$

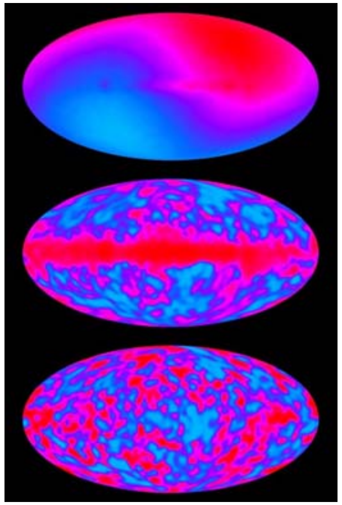
The integral is $\pi^4/15$ so that

$$\varepsilon_{\rm rad} = \frac{8\pi^5 k^4}{15 h^3 c^3} T^4 = a T^4$$

$$a = \frac{8\pi^5 k^4}{15 h^3 c^3} = 7.566\times10^{-16}\ {\rm J\ K^{-4}}$$

This is known as Stefan's Law.

5.4 The microwave background



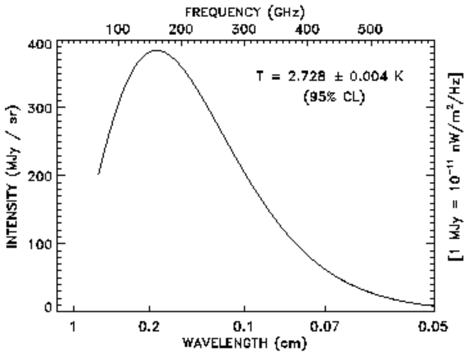
The dipole component of the Cosmic Microwave background, showing redshifted and blue-shifted components corresponding to our motion with respect to the standard of rest defined by the CMB

The fluctuations in the CMB after subtraction of the dipole component. The central strip corresponds to emission from the Galaxy

Fluctuations in the CMB after a model for emission from the Galaxy has been subtracted has been subtracted.

Credits: NASA: http://windows.ivv.nasa.gov/cgi-bin/tour_def/the_universe/CMBR.html

5.5 The spectrum of the microwave background



Spectrum of the microwave background as measured by COBE. The fit to a Planck spectrum is extremely good.

Credits NASA

http://map.gsfc.nasa.gov/html/

5.6 Energy density of the microwave background

The microwave background is measure to have a temperature of $T = 2.728°{\rm K}$. The corresponding energy density is $\varepsilon_{\rm MWB} = 4.2\times10^{-15}\ {\rm J\ m^{-3}} = 2.62\times10^{5}\ {\rm eV\ m^{-3}}$. This energy density is important when we come to consider the emission resulting from the scattering of these photons by relativistic electrons.

6 Aspects of stellar evolution

See Longair, Vol. 2, for much more detailed information.

6.1 Stars in isolation

- Main sequence stars with $M \sim$ Solar Mass evolve to white dwarfs -> Planetary Nebulae
- Higher mass stars evolve to Neutron stars or Black Holes -> Pulsars, Supernovae or Hypernovae
- Supernovae heat the ISM and create cosmic rays. Most cosmic rays may be the result of supernovae blast waves. Pulsars may also contribute to injection of fast particles into the ISM
- Hypernovae may be the parent objects of γ–ray bursters
- γ–ray bursters may also result from BH-BH, or BH-NS mergers

6.2 Binaries

- Approximately half of the stars in the Galaxy may be in the

form of binaries

- Periods range from a few hours to $\sim 10^3$ yrs (upper limit really unknown)
- Close binaries have orbital separations of the order of few times the radii of the stars to separations in which the stars have a common envelope (contact binaries).

Masses of stars in binaries

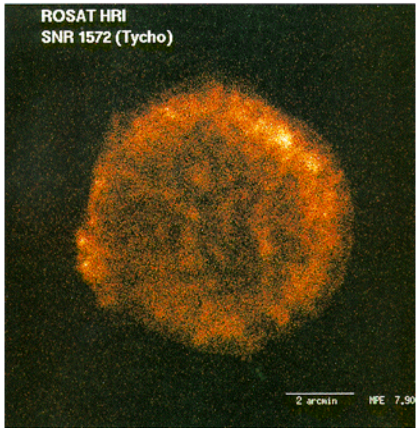
- Massive binaries consisting of O and B type stars
- Intermediate mass binaries
- Systems with compact stars – White dwarfs, Neutron stars and Black Holes

Symbiotic stars

- Evolution can lead to mass transfer from binary onto companion and subsequent evolution of companion. e.g. Mass transfer from Red Giant can lead to main sequence star evolving to neutron star.
- Further mass transfer results in accretion disc
- Cataclysmic variables – Accretion disc about white dwarf
- X-ray binaries – Evolved main sequence star + neutron star or black hole

7 Supernovae

7.1 Image of a supernova remnant



Supernova Remnant Tycho (SNR 1572)

In AD 1572, the Danish astronomer Tycho Brahe observed the explosion of a star in the Milky Way. Today, we see with ROSAT in great detail the expanding shell of the ejecta running into the interstellar environment at about Mach 150 and thereby being heated up to millions of degrees. This picture was taken with the High Resolution Imager (HRI).

Supernova remnants are useful laboratories for the study of many high energy phenomena, as well as being objects of interest in their own right.

They are probably the source of most of the high energy particles (cosmic rays) in the interstellar medium.

7.2 Stages in the evolution of a supernova remnant

1. **First phase - The Piston phase.** Star explodes - piston of expanding debris sweeps up surrounding interstellar medium. Sometimes this involves the wind from a previous phase (e.g. red giant phase) of the star.

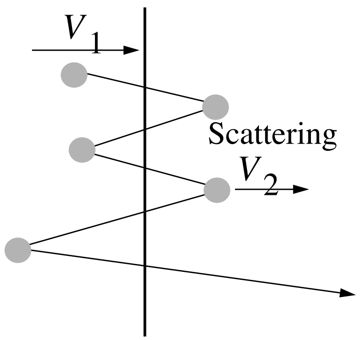
2. **Second Phase - Sedov-Taylor Phase.** The mass of swept up matter becomes comparable to the mass of the star. The solution describing the expanding remnant starts to "forget about" the initial conditions. The solution becomes determined by the energy of the original explosion and the conditions (mainly density) in the circumstellar medium. This is know as the Sedov-Taylor phase (after the hydrodynamicists who studied

this particular form of similarity solution).

3. **Third Phase - Snowplough phase.** The blast wave which throughout the Sedov-Taylor phase has been decelerating, gets to the stage where the temperature drops below about 10^6K. Line emission then starts to dominate the cooling, the shock wave becomes radiative and material starts to pile up behind the shock.

4. **Fourth phase - Subsonic phase.** The blast waves decelerates to the extent where it becomes subsonic and the remnant is dispersed by random motions.

7.3 Radio emission from supernova remnants



The radio emission from supernova remnants results from synchrotron emission from relativistic particles which are "accelerated" in the shock front.

The particle gains a certain amount of energy per shock crossing and crosses the shock a number of times before escaping downstream.

This process leads to a power-law distribution of particle energies with the number per unit energy being given by $N(E) \propto E^{-a}$.

The above qualitative description of *diffusive shock acceleration* is probably also relevant to the acceleration of particles in other cosmic environments such as Active Galactic Nuclei.

8 Active Galactic Nuclei

High energy astrophysics is extremely important for understanding many of the physical processes occurring in Active Galactic Nuclei. There are many types of AGN although one of the goals of the last decade or so has been to unify many of the different varieties of AGN. The following is a brief summary of the main properties:

8.1 Radio galaxies

The first radio galaxies were discovered in the late 1940s. The increasing resolution of radio interferometers has meant that we have been able to conduct more and more detailed models of them – especially over about the last 20 years.

The radio galaxy Fornax A. The optical galaxy is represented in blue; the radio emission is represented in red.

Radio galaxies come in 2 flavours - Fanaroff-Riley class 1 and Class 2 (FR1 and FR2 for short). The FR1s of which the picture at the left is an example show radio morphology consisting of "woofly" lobes. These are the least powerful of the radio galaxies. The most powerful

radio galaxies of which Cygnus A is the prototype show obvious edge-brightened structure and hotspots.

8.2 FR1 & FR2 radio galaxies

Fanaroff and Riley in 1974 classified radio galaxies into two types in the following way:

- Use the image of the radio galaxy to define the extent of the source on each side of the core.
- Class 1 radio galaxies are those in which the brightest part of the image is located at a distance from the core which is *less* than 50% of the source extent.
- Class 2 radio galaxies are those in which the brightest part of the image is located at a distance from the core which is *greater* than 50% of the source extent.

This classification has an important bearing on radio source physics. Following are examples of FR1 and FR2 radio galaxies.

FR1 example: 3C31 (http://www.cv.nrao.edu/~abridle/)

- Red: VLA radio images; Blue: optical images
- Left: VLA 21cm image at 5.5 arcsecond resolution superposed on Digitized Palomar Sky Survey E print
- Right: VLA 3.6cm radio image at 0.25 arcsecond resolution superposed on Hubble Space Telescope FOC image
- FR 1 (plumed) radio galaxy at z=0.0169 (51/h

FR2example: 3c219 (http://www.cv.nrao.edu/~abridle/)

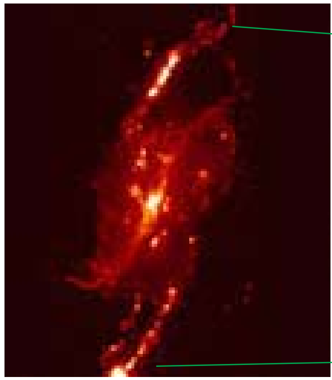
- FR 2 (double-lobed) radio galaxy at z=0.1745 (544/h Mpc, H = 100h km/s/Mpc)
- Filamentary lobes extending several hundred kpc
- Bright, extended hot spots in both lobes
- Abbreviated (restarting?) jet and counterjet
- Red/yellow: VLA 1.4+1.6 GHz combined image at 1.4 arcsecond resolution
- Blue: Optical V band image from Stefi A. Baum, Timothy Heckman,

8.3 Seyfert galaxies

Seyfert galaxies are generally disk or spiral galaxies which are characterised by starlike nuclei. They also often show radio emission at a low level but are about a thousand times weaker than

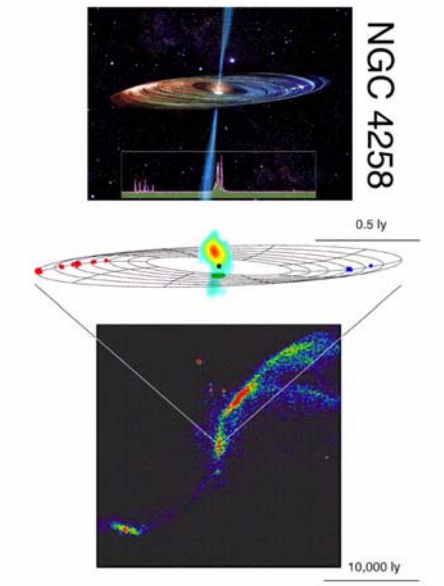
classical radio galaxies.

The Seyfert galaxy NGC 4258



The inner part of the Galaxy NGC 4258

http://sousun1.phys.soton.ac.uk/PH308/

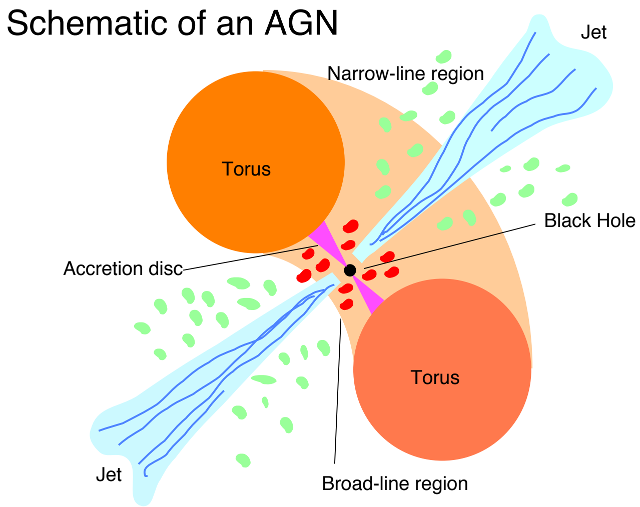


The Seyfert Galaxy NGC 4258 which has been studied intensively by Greenhill, Moran and colleagues. This galaxy has well observed maser spots whose velocity, when imaged at high resolution, show evidence for a black hole with $M \approx 10^7$ solar masses.

The lower image is a VLA radio image of the Seyfert galaxy NGC 4258 with about 1 arcsecond resolution. This shows the large scale jets in this galaxy.

The middle image is a VLBI image at a few mas resolution showing the inner jet and the red-shifted and blue-shifted maser spots. The wire frame plot represents a model of a warped accretion disk.

The top image is an artists conception of the relation between the jets and the accretion disk.



Seyfert galaxies are in general spiral or disk galaxies and are an example of “radio quiet” AGN. However, they have bright optical emission coming from the core and their cores are also bright X-ray emitters. The optical emission originates both from starburst activity and from optical emission from an accretion disk surrounding a black hole.The X-ray emission is believed to originate from a hot corona above the black hole accretion disk.

9 Unified schemes

9.1 Seyfert 1 and 2 galaxies

Early models of Seyfert galaxies involved spherically symmetric models. One of the greatest advances of the last few years has been the recognition that active galactic nuclei are at best axisymmetric and that many nuclei may be surrounded by a torus as indicated in the following picture.

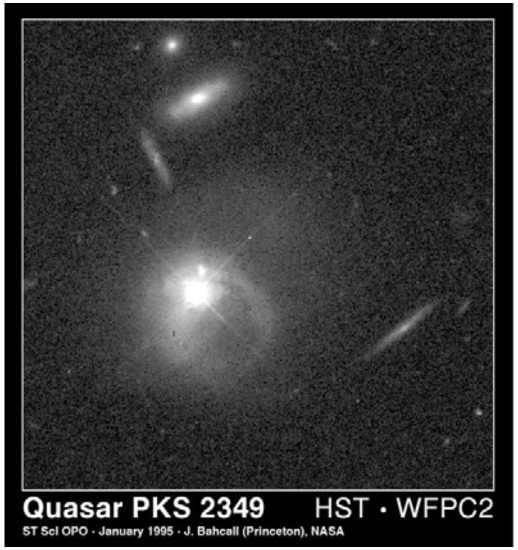
Viewed from above the torus, one sees into the environment of the black hole (which cannot be resolved) and the Broad Line Region (BLR). In the Unified Scheme this defines a Seyfert 1 galaxy

which has broad permitted lines of $H\alpha$, $H\beta$ etc. The Narrow-Line Region (NLR) exhibits narrow forbidden lines of [OIII] and other species as well as narrow permitted lines.

For a Seyfert 2, on the other hand, one is viewing from the side and the BLR is obscured. One only directly sees the NLR but sometimes the BLR is visible through indirect scattered light detected through polarimetry.

Typical broad line widths are ~ 10,000 km/s whereas typical narrow line widths are ~ 1,000 km/s.

9.2 Quasars and FR2 radio galaxies

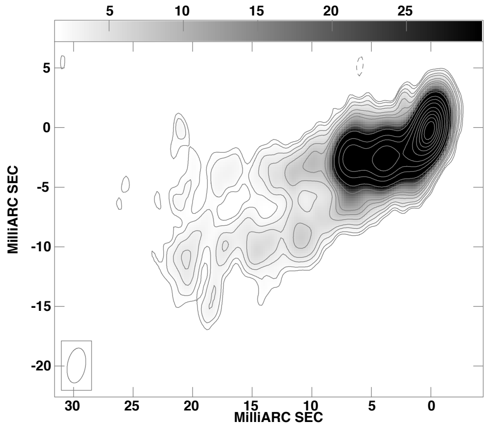


The acronym QUASAR originally stood for Quasi Stellar Radio Source. although many of the current quasars are radio quiet. Typically only about 5% of Quasi-stellar objects (QSOs) are radio loud and the occurrence of radio quietness and radio loudness is one of the outstanding problems in the field.

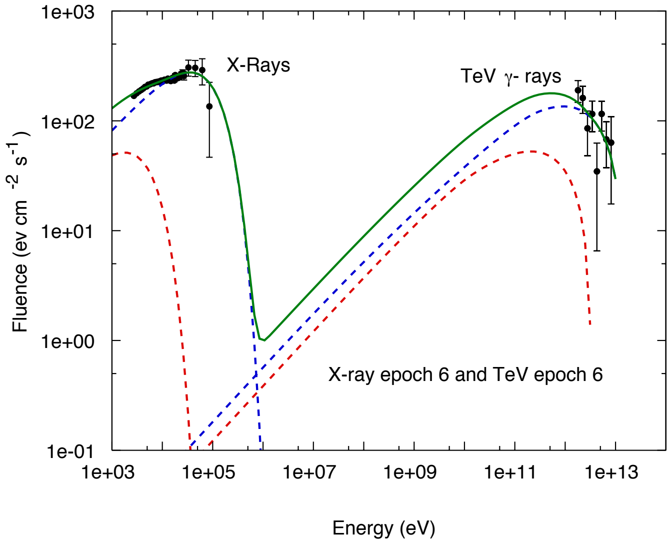
In the pre-HST era the existence of galaxy-like "fuzz" around quasars was becoming apparent. With the advent of HST, however, this fuzz is becoming resolved and here we see possible evidence for relation of the quasar PKS 2349 to a merger - indicated by the tidal tail.

In the Unified Scheme, QUASARS are FR2 radio galaxies viewed at small to modest angles $< 45°$ to the line of sight.

9.3 BL-Lac objects and FR1 radio galaxies



Space VLBI image (Giovannini et al.) of the BL-Lac object Markarian 501. One of the components near the core is moving with an apparent velocity of $6.7c$.



Description of above spectrum

The X-ray and TeV spectrum of MKN 501. The X-rays originate from a region about 10^{16} cm in size and are due to synchrotron emission. The TeV γ-rays are the results of scattering of low energy photons off the high energy electrons responsible for the X-rays.