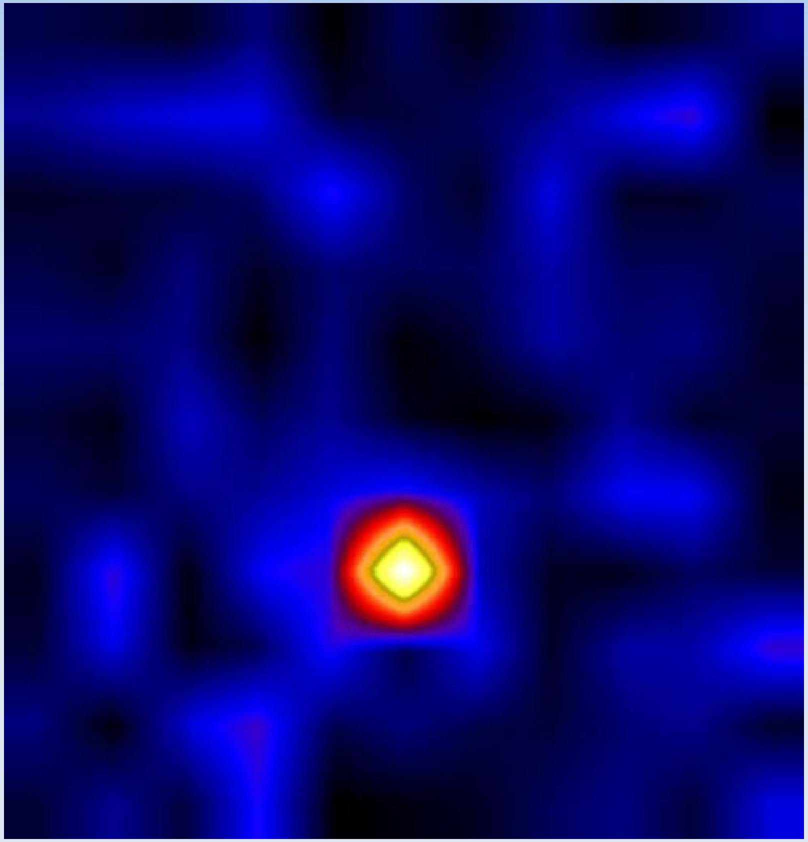
Compact Stars



Lecture 6

Summary of the previous lecture

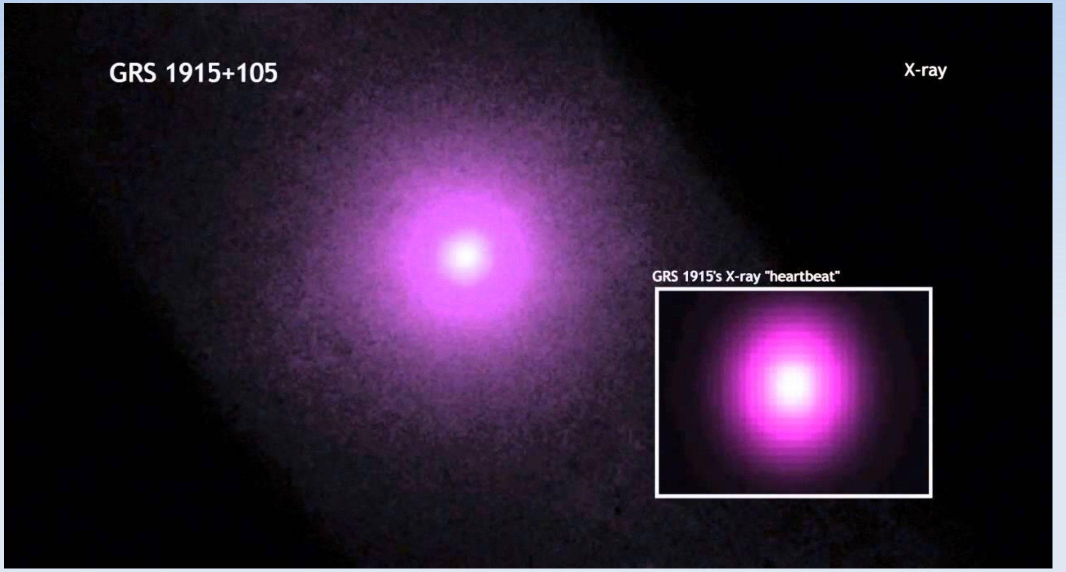
- I presented the systems with accreting white dwarfs – cataclysmic variables - and their classification.
- I showed that about the time-dependent modeling of accretion disk thermal-viscous instabilities, induced by the partial hydrogen ionisation can explain the dwarf novae outbursts. The opacity change in disk affects thermal balance and leads to instabilities.
- The dominant radiation pressure (in black hole or neutron star X-ray binaries) may lead to similar cycles, for hotter disks. In the radiation pressure dominated disk some stabilisation is needed (to form an upper branch on the stability ”S-curve”). It is provided by the advective model (slim disk).
- The instabilities of the accretion flows manifest in quasi-periodic oscillations of luminosity. Examples: dwarf novae (best fitted with two values of viscosity parameter), microquasars.

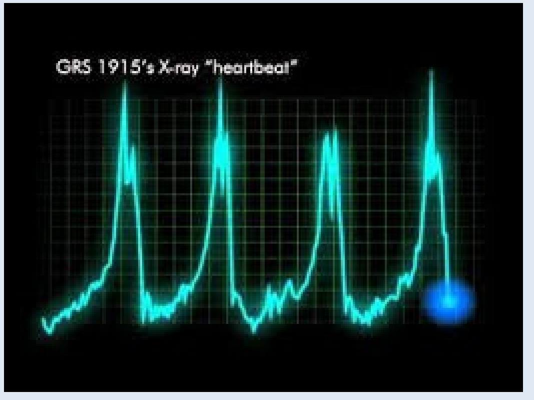
Microquasars, quasars, and other jet sources

- Today we will start from microquars
- Some of them exhibit the radiation pressure instability in action, and oscillations in the accretion disks at high accretion rates (close to Eddington limit)
- Their primary feature are the relativistic blobs of plasma ejected along the symmetry axis
- They are similar to quasars, and other astrophysical jet sources, but on stellar mass scale.

GRS 1915+105

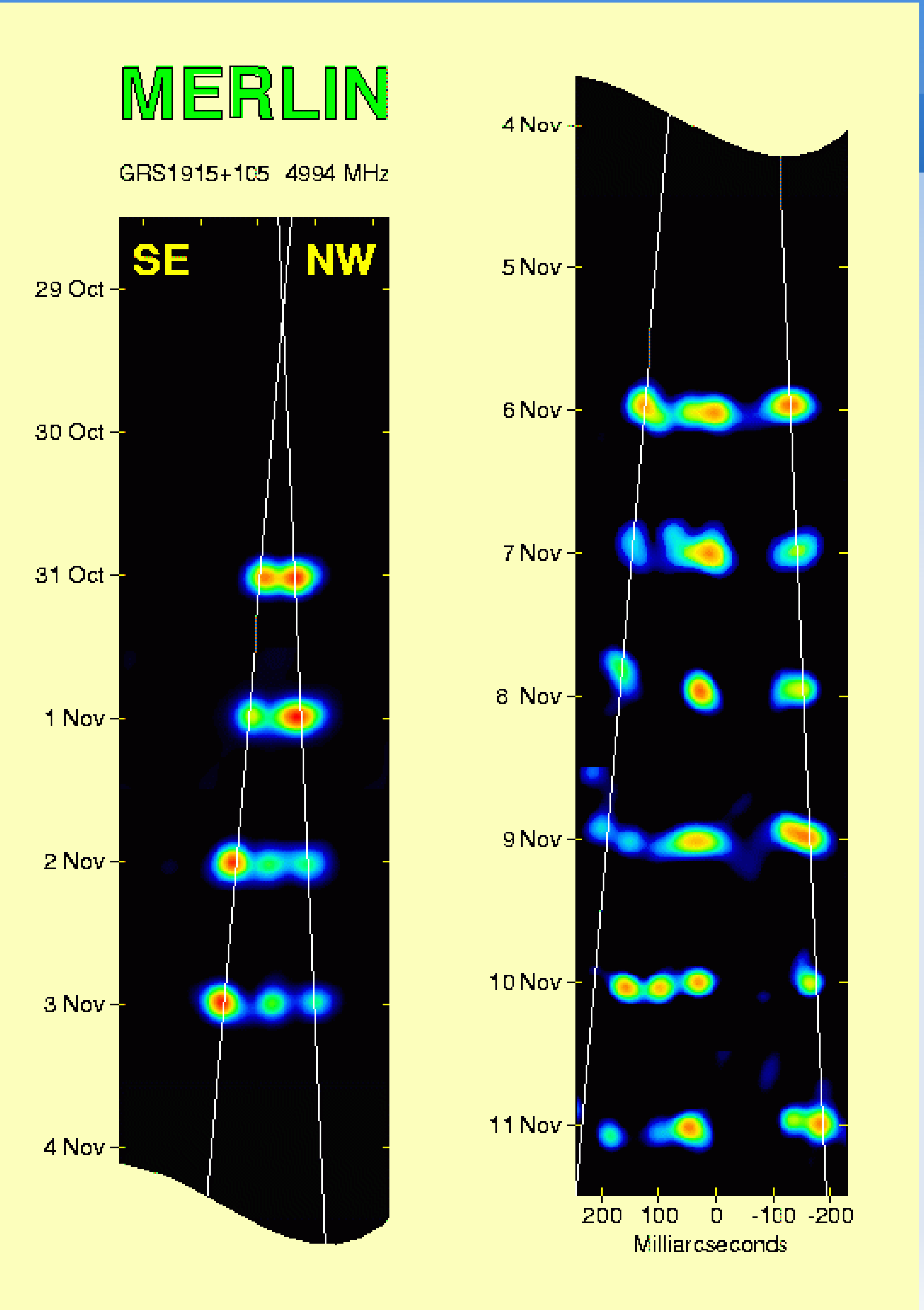
- Accreting black hole, almost Eddington luminosity
- Radiation pressure instability in action: limit-cycle oscillations of X-ray luminosity
- Exhibits radio jets: analogous to quasars
- Interesting source to study jet-disk connection





GRS 1915+105

Radio observations from 1994 (revealed apparent superluminal motion)



Apparent superluminal motion

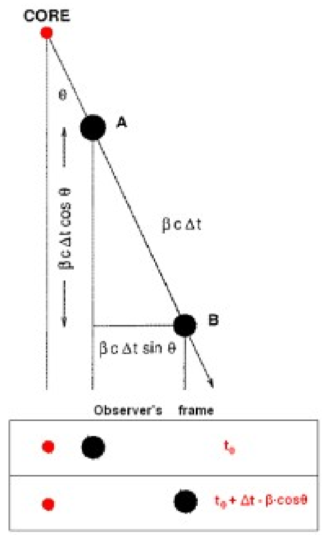


Figure 3. Cartoon illustrating the superluminal motion phenomenon. *From R.A. Laing* [14].

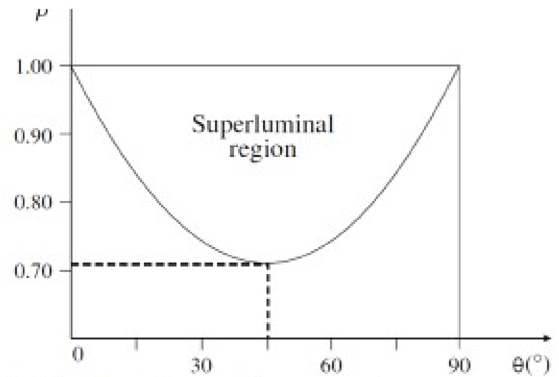


Figure 4. Superluminal region for a linearly expanding source, shown as an area on the $\beta - \theta$ diagram. *From D.F. Falla & M.J. Floyd* [15].

- $\Delta t_{obs} = \Delta t_{em} - d/c$
- $d = v\, \Delta t_{em} \cos\theta$

$$v_{obs} = v \sin\theta \;\; \Delta t_{em} / \Delta t_{obs}$$

$$= \beta\, c \sin\theta / (1 - \beta \cos\theta)$$

β_{obs} = 1.26 for
β=0.92 and θ=70°

Microquasars

Known from 1990-ties

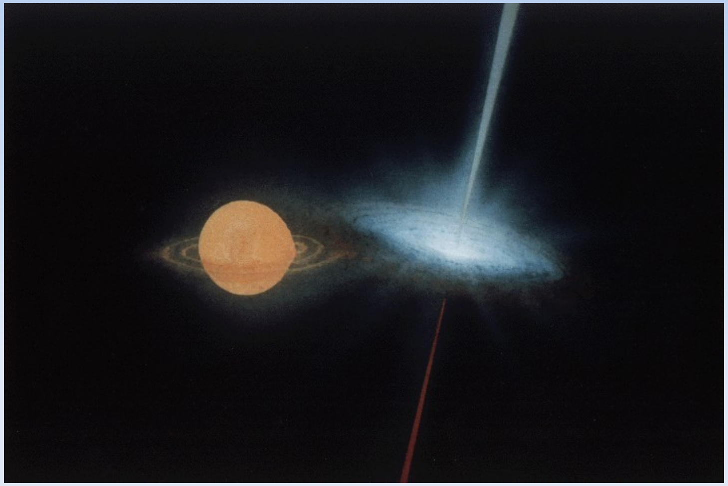
Smaller “cousins” of quasars

Characteristics:

•Strong and variable radio emission

•Presence of jets

•Large X-ray luminosity



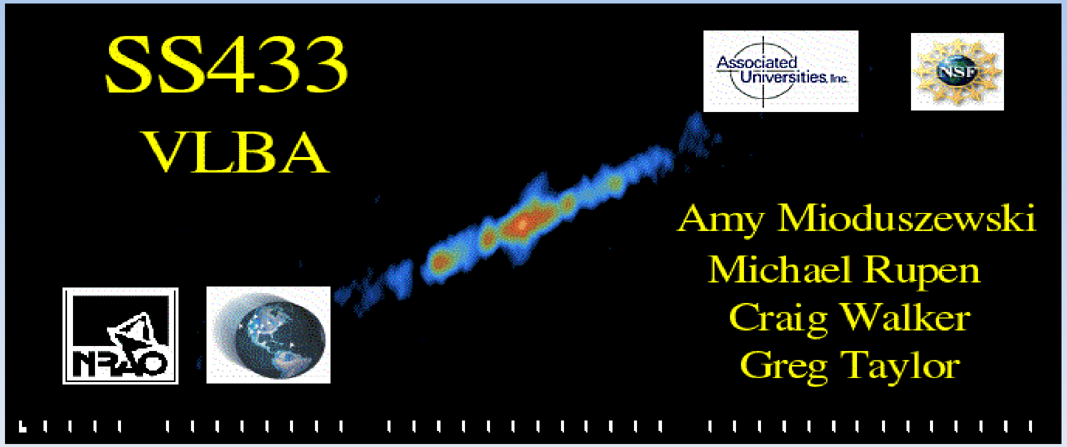
The energetics is explained by a black hole accretion

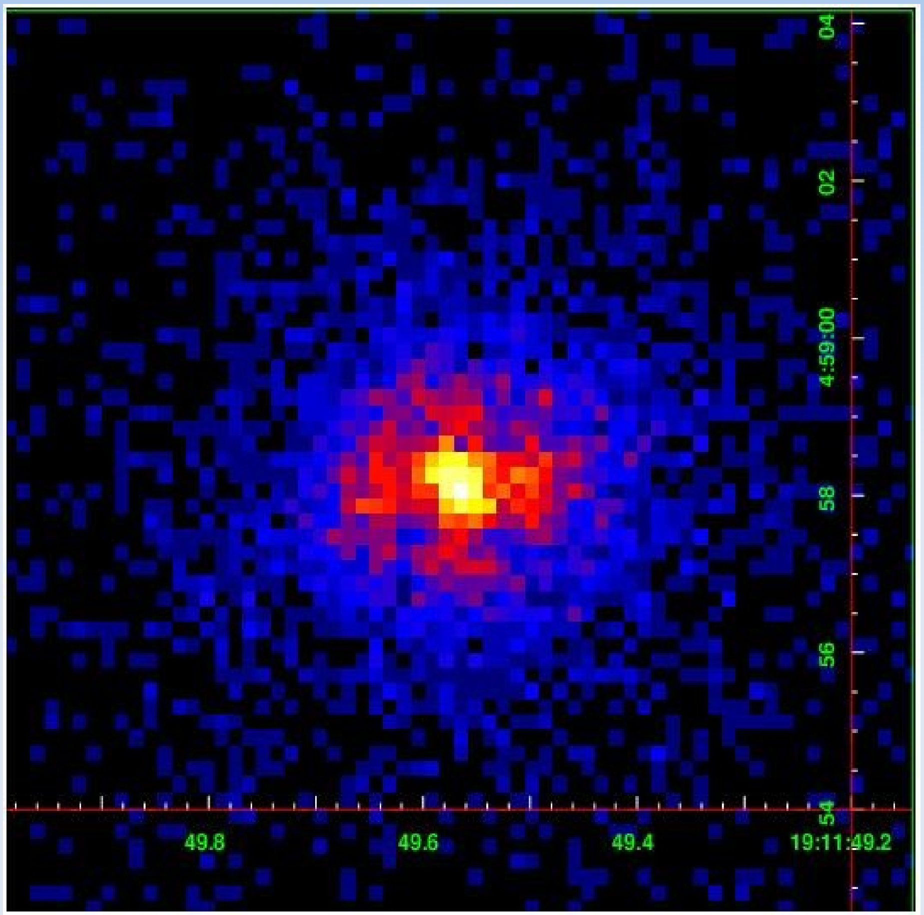
Simultaneous radio-X-ray observations allowed the identification of radio jets with X-ray binaries (GRANAT and VLBA)

Many are known: over 30 sources including Integral data (as of 2017)

(http://www.aim.univ-paris7.fr/CHATY/Microquasars/microquasars.html)

Microquasars: prototype of the class





SS 433 – first microquasar discovered (Margon et al. 1979). Chandra X-ray image

SS 433 in radio

- Microquasar with NS
- Detected by VLA (Hjellming & Johnston 1981)
- Mildly relativistic, v~0.26 c
- Precessing jet model proposed

L144 HJELLMING AND JOHNSTON Vol. 246

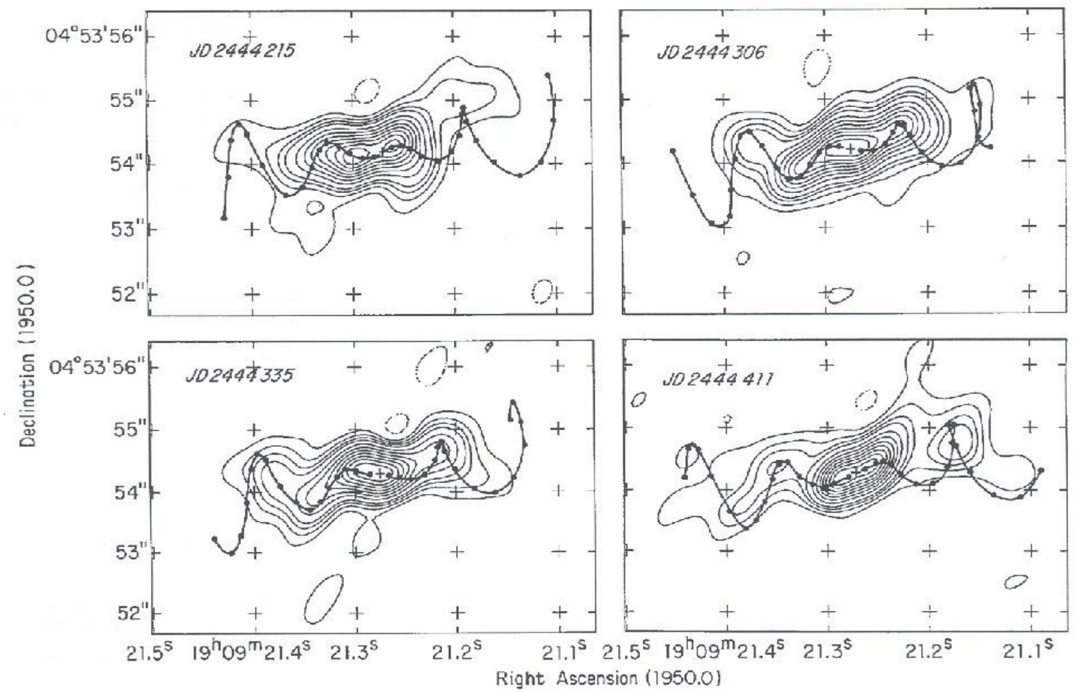
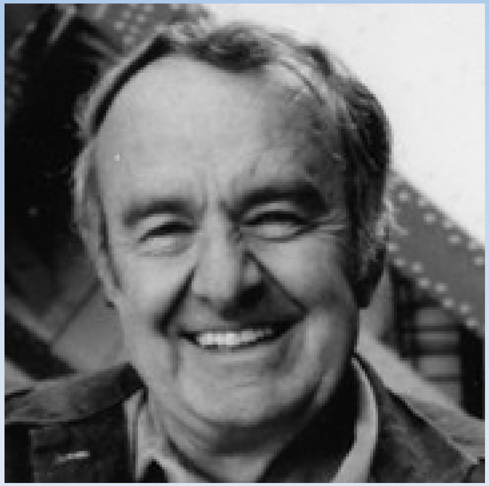


FIG. 2.—VLA radio contour maps of SS 433 at 4885 MHz for t=JD 2,444,215, 2,444,306, 2,444,335, and 2,444,111 are displayed in a form where the unresolved core radio source (small +) is removed, and the proper motion paths of material ejected at 20 day intervals with the parameters of Table 1 are drawn with filled circles. The contour levels correspond to 90, 80, 70, 60, 50, 40, 30, 20, 15, 10, 5, and −5% of the peak flux density values of 0.070, 0.030, 0.029, and 0.032 Jy per beam area for JD 2,444,215, 2,444,306, 2,444,306, and 2,444,411 maps, respectively.

Quasars: definition



Allan Sandage

Discovered in 1960-ties

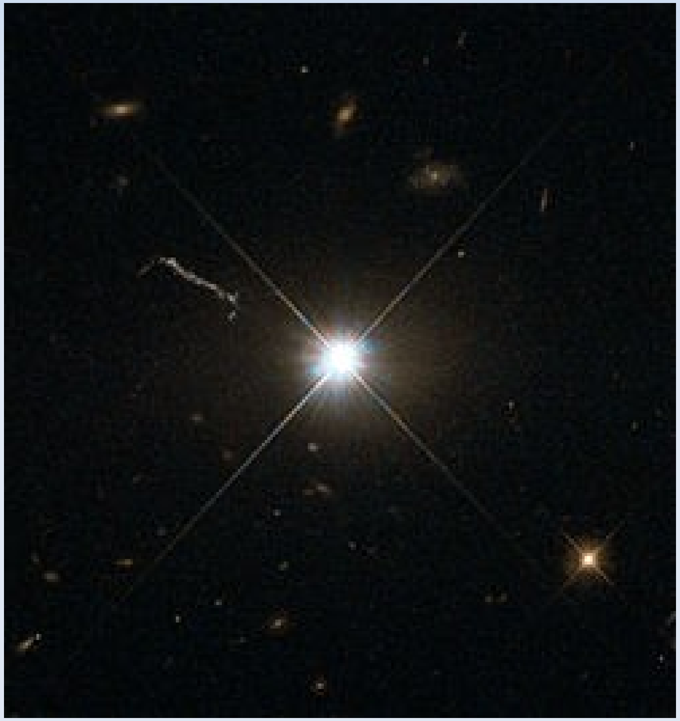
Quasi-Stellar Radiosources

Currently about 1 000 000 known (many dicovered SDSS survey)

About 10% of them are radio loud

Matthews T., Sandage A., et al. (1963, ApJ): Optical identification of 3C 48

Schmidt M. & Oke B. (Nature, 1963): Z=0.158 in 3C 273



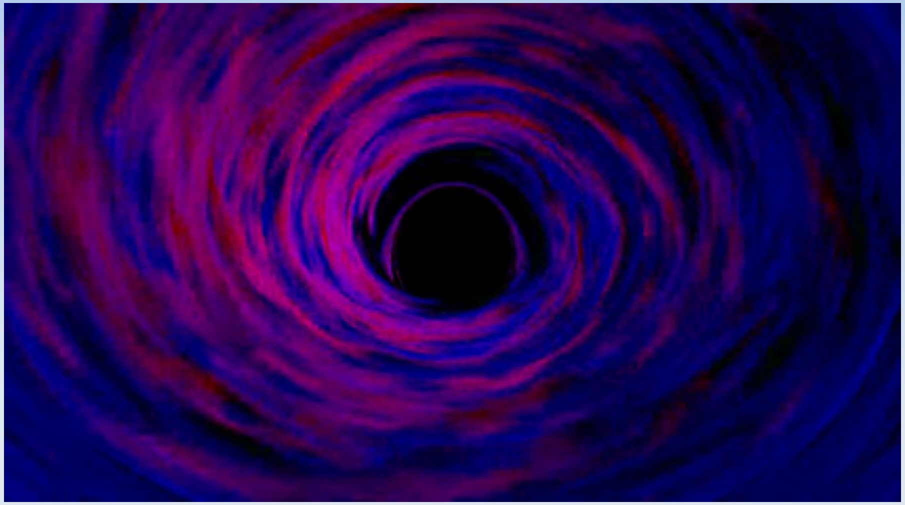
3C 273 – image from Hubble Telescope

Energy source of quasars

Quasars shine at all electromagnetic spectrum, from IR to X. (and Radio i Gamma)

The luminosity of a QSO can be 100x higher than a galaxy

Fast variability of flux indicates that the emitting region is very compact (spatial scale of a Solar System)



Accretion onto black hole
E_p=GMm/R

Size and timescale proportional to M_{BH}

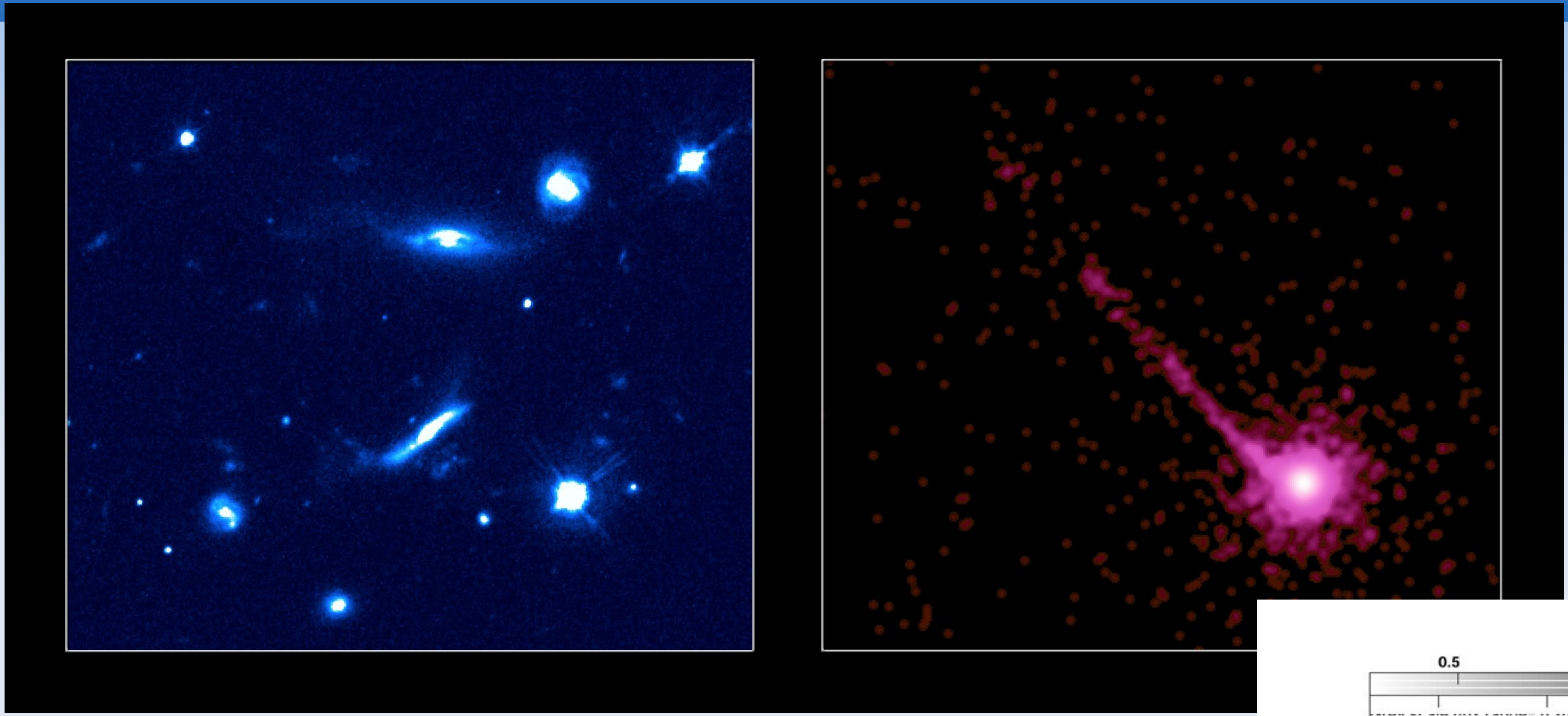
$R_{schw} = 2GM_{BH}/c^2$;

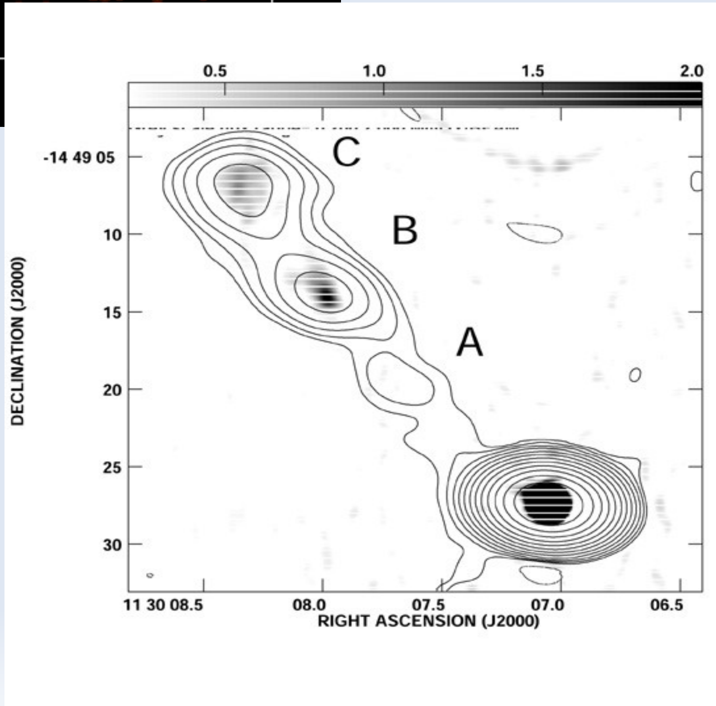
$\Delta T \sim M_{BH}$

Efficiency $E_p/mc^2 = GM/Rc^2$

Quasars emit jets

PKS 1127-145



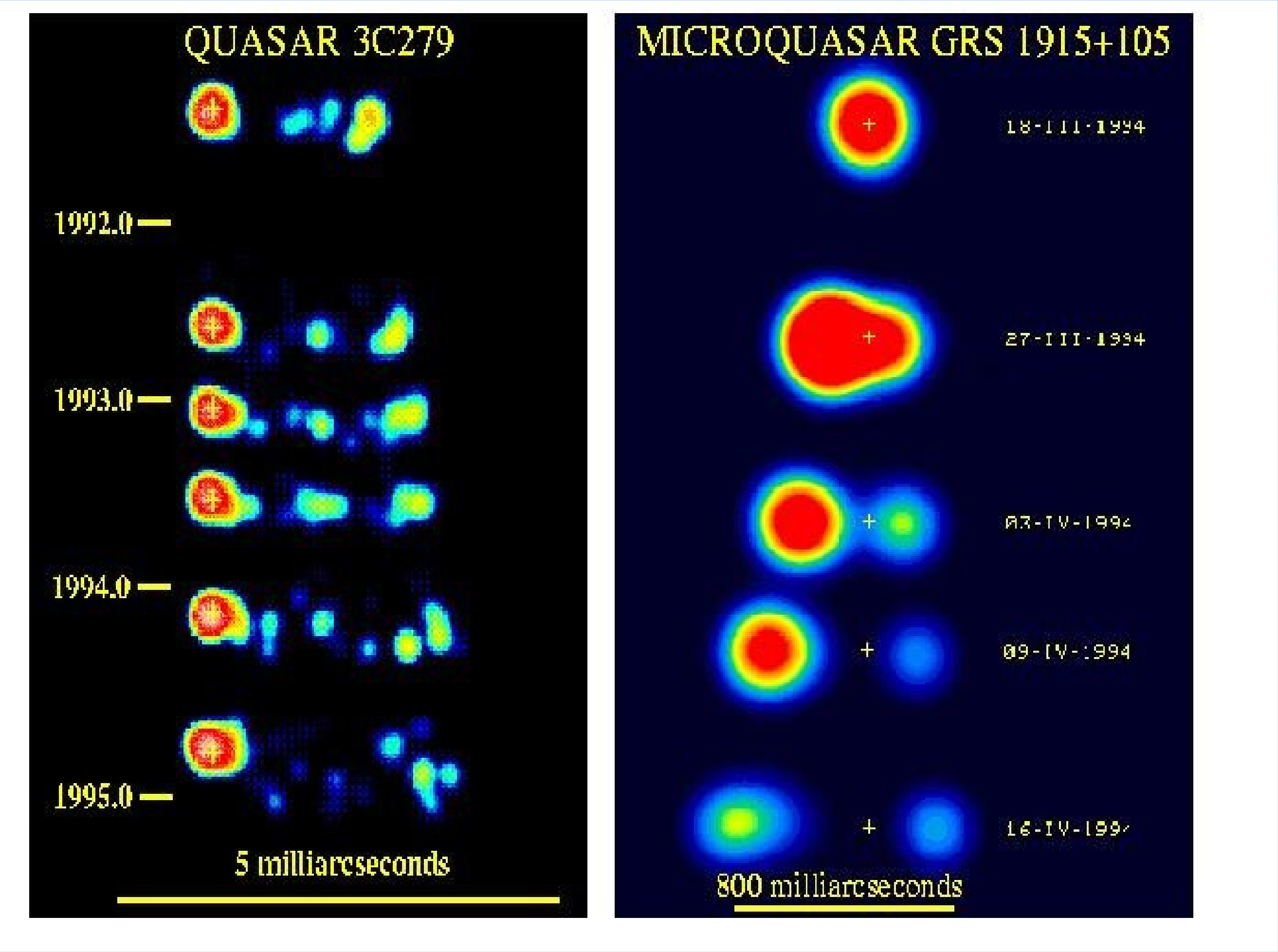


Quasar PKS 1127-145,
X-ray image from Chandra
(Siemiginowska & Bechtold, 2000)
Optical (HST), radio (VLA)

Large scale jet has size of million light years

Microquasars

- Defined by the analogy to quasars
- Radio observations of jets show apparently superluminal motions



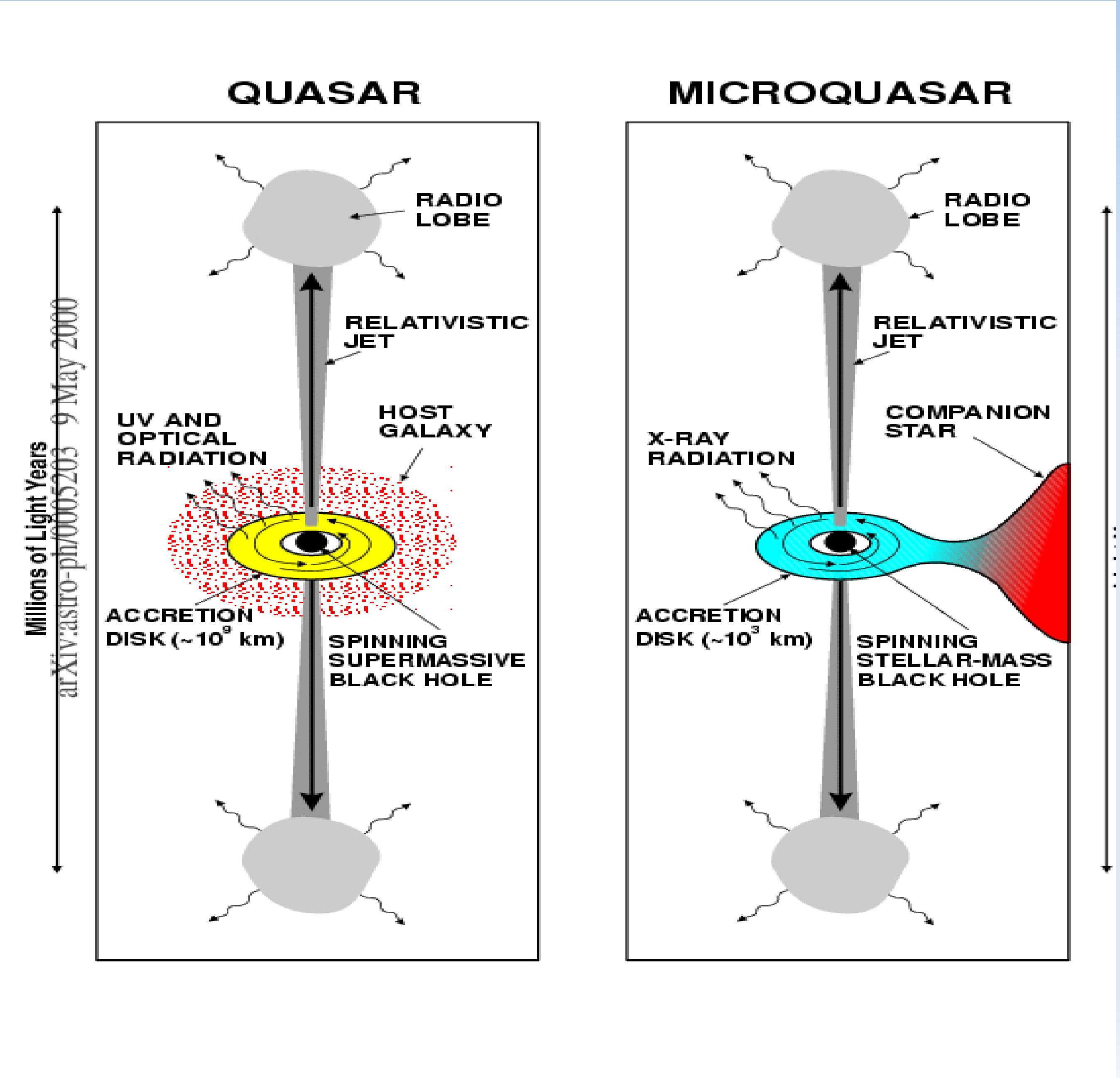
Mirabel & Rodriguez, 1994, Nature

Comparison QSOs vs. μQSOs

- Point radiosources, discovered in 1960's
- Active nuclei of galaxies
- Mass of BH 10^8 - 10^9 M_{Sun}
- T_{disk} ~ 10^5 K
- Luminosity ~ 10^{47} erg/s
- Accretion rate ~ 10 M_{sun}/yr
- Variability in timescale of years
- Jet range about 10^7 light years

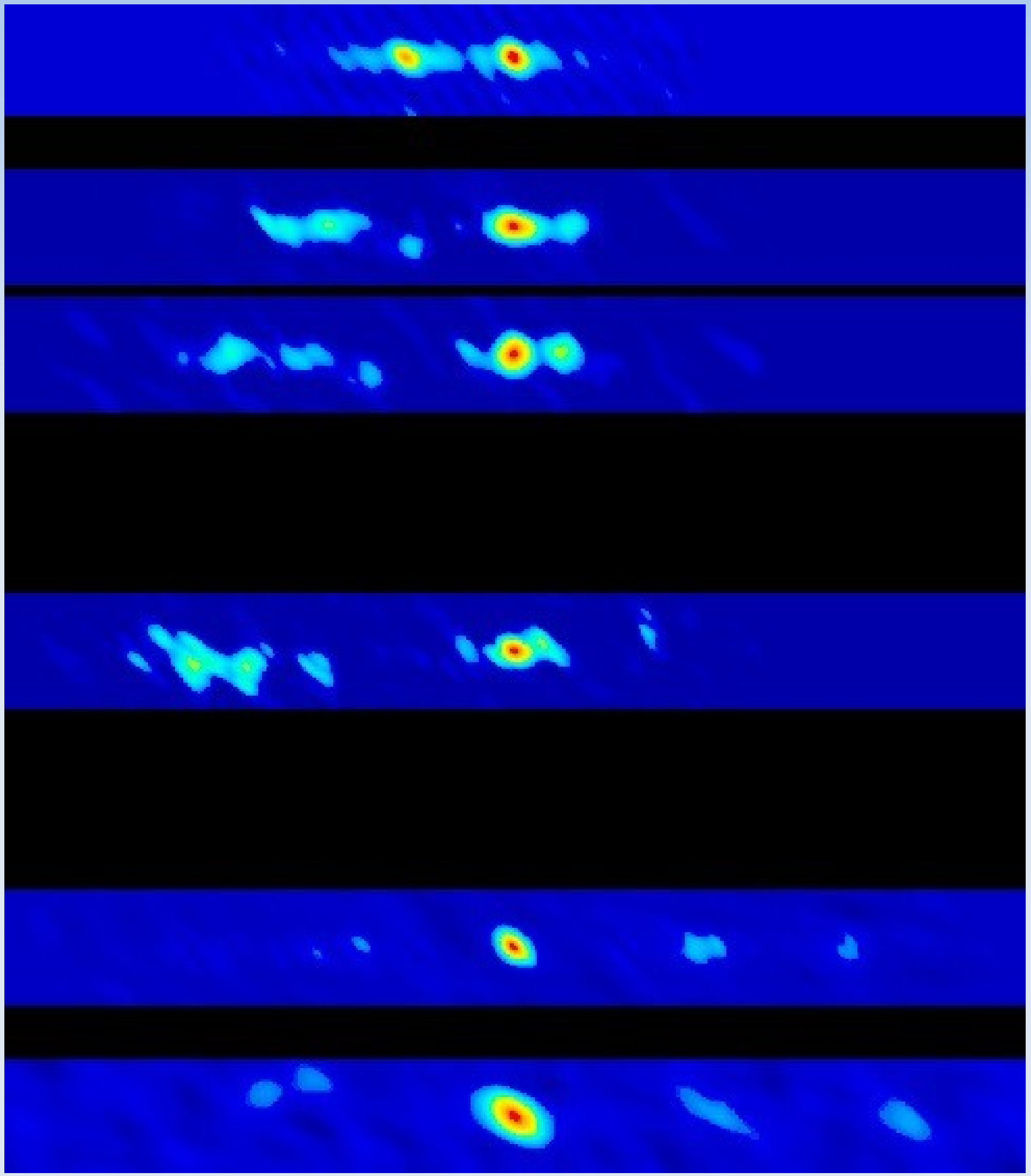
- Discovered in our Galaxy in 1990's
- Binary stars systems
- Mass of BH/NS 2 - 20 M_{Sun}
- T_{disk} ~ 10^7 K
- Luminosity ~ 10^{37} erg/s
- Accretion rate ~ 10^{-9} M_{sun}/yr
- Variability in timescales of minutes
- Jet range of several light years

Comparison of Quasars and Microquasars



Second superluminal BH XRB

- GRO 1655-40
  - microquasar
  - VLBA radio data
  - Apparently superluminal motions
  - Observed after the X-ray outburst



Expanding blobs

- From observations we know proper motions of the approaching and receeding blobs (in arc seconds per day). This gives the expansion velocity times the cosinus of the angle between jet and our line of sight.
- Knowing the distance to the source, we can independently determine the jet velocity and viewing angle.
- The jet velocity can be also measured from the observations of emission lines.

Synchrotron radiation

- High brightness temperatures, ‘nonthermal’ spectra and polarisation measurements indicate an origin as synchrotron emission from relativistic electrons

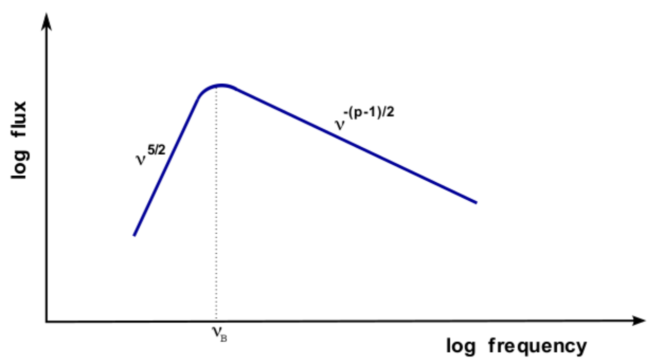
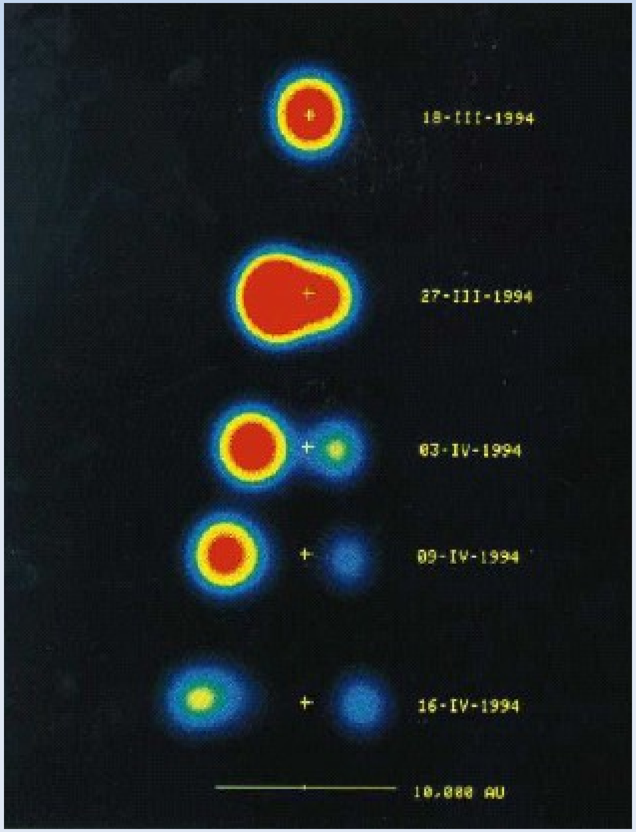


Figure 2: Total synchrotron spectrum - Shape for electron power law $n(\gamma) \propto \gamma^{-p}$, with $j_\nu \propto \nu^{5/2}$ in the low-frequency, optically-thick regime ($\nu < \nu_B$), and $j_\nu \propto \nu^{-(p-1)/2}$ in the optically thin ($\nu > \nu_B$) regime. Note that for an electron distribution with low- and high-energy cut-off γ_{min}, γ_{max}, the optically thin spectrum could be more complex with low-frequency part $j_\nu \propto \nu^{1/3}$, mid-frequency part $j_\nu \propto \nu^{-(p-1)/2}$ and high-energy frequency part $j_\nu \propto e^{-\nu/\nu_{max}}$, $\nu_{max} \simeq \gamma_{max}^2 \nu_L$.

6

Observed optically thin spectral indices
$-0.4 \geq \alpha \geq -0.8$, indicate
$1.8 \leq p \leq 2.6$
for the underlying electron distribution

Doppler boosting



$S_{r,a} = S_0 / [\gamma\ (1 \pm \beta \cos\theta)]^{k+\alpha}$

$S_0 \propto \nu^{-\alpha}$ radiation flux density in the source frame;

k=2 for steady jet or k=3 for ’blobby jet”

For small angles and large luminosities, the apparent brightness of approaching blob is boosted, (a), and for receeding blob it is weakened, (r)

Inverse Compton process

Total radiated IC power for single electron (Thomson regime, $\epsilon_i = \gamma h\nu \ll m_e c^2$)

$$P_{IC} = 4/3\ \gamma^2\ \beta^2\ \sigma_T\ c\ U_{rad}$$

This is similar to single particle synchrotron power:

$$P_{syn} = 4/3\ \gamma^2\ \beta^2\ \sigma_T\ c\ U_B$$

Reason: In both cases, electron is accelerated by an electric field which it observes in its instantaneous rest-frame (electromagnetic wave/photon, $\mathbf{E}' = \mathbf{v} \times \mathbf{B}$).
Electron does not care about true origin of electric field.

Spectral index of scattered photon spectrum:

$$P_{IC}(\nu) \propto \nu^{-\alpha}$$

off power-law electron distribution with index p, $n_e(\gamma) \propto \gamma^{-p}$, is

$$\alpha = (p - 1)/2$$

This is similar to synchrotron as well.

Compton upscattering of synchrotron photons by the electrons themselves (SSC) preserves the spectral index in the Thomson regime

$$\alpha_{syn} \approx \alpha_{IC}$$

Two main radiative processes

Ratio of the **Inverse Compton** to the **Synchrotron** flux density, for a fixed magnetic field strength, as a function of the jet viewing angle.

Depends on the jet bulk Lorentz factor and synchrotron power-law spectral index α (1.1 and 0.6, with dashed and solid lines).

See ”Radiative processes in astrophysics”, Rybicki & Ligthman

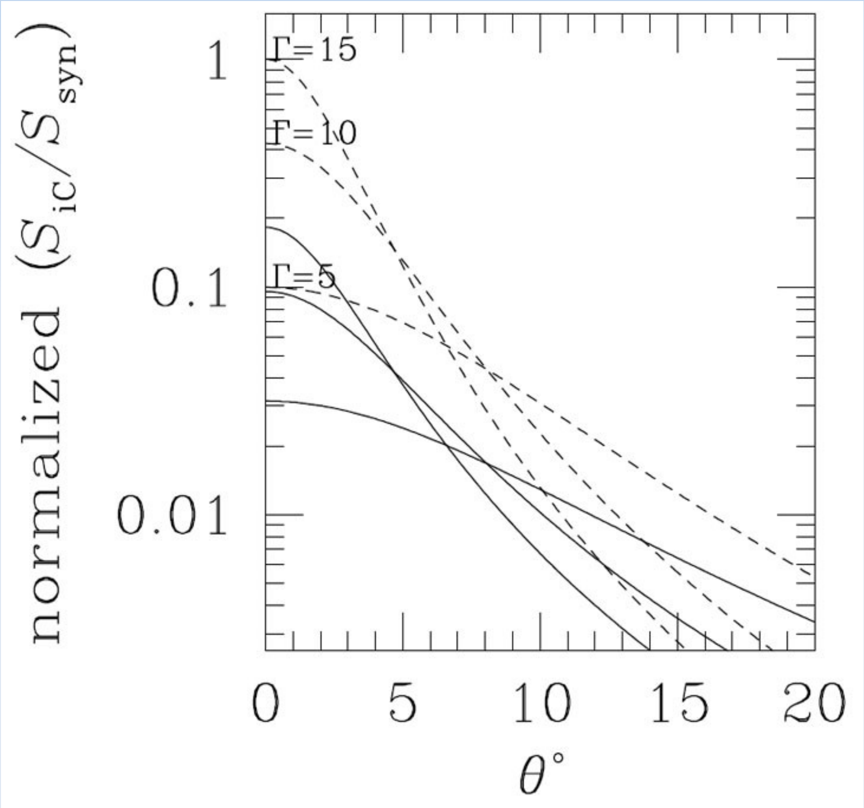


Figure from Worrall & Birkinshaw, 2006, ”Lecture Notes in Physics”

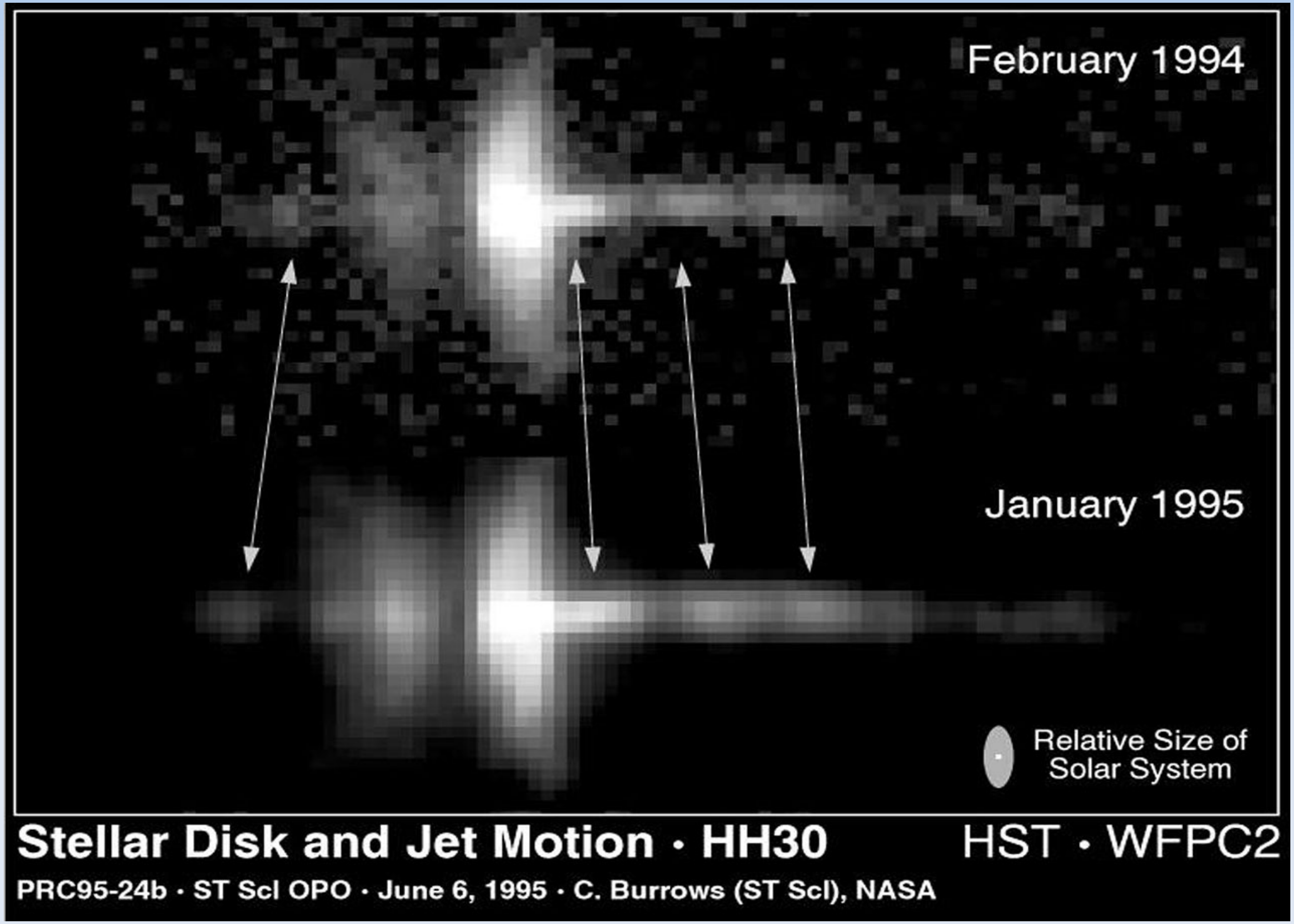
Break

Systems producing jets

- Jets are observed in a number of types of sources:
  - Young stellar objects
  - Massive X-ray binaries
  - Black hole X-ray transients
  - Low mass X-ray binaries
  - Symbiotic stars
  - Planetary nebulae
  - Supersoft X-ray sources
  - Active galactic nuclei

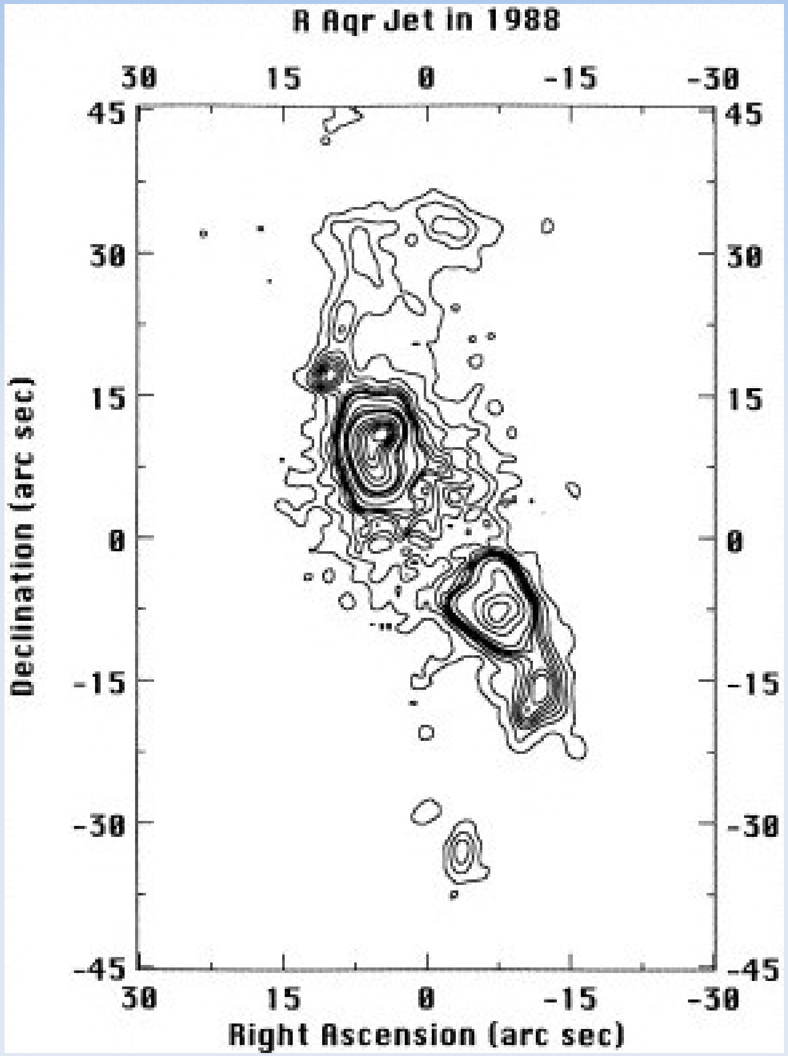
Examples: YSO

- Herbig-Haro object
- Young star surrounded by a thin disk
- Vjet = 100-350 km/s



Examples: R Aqr

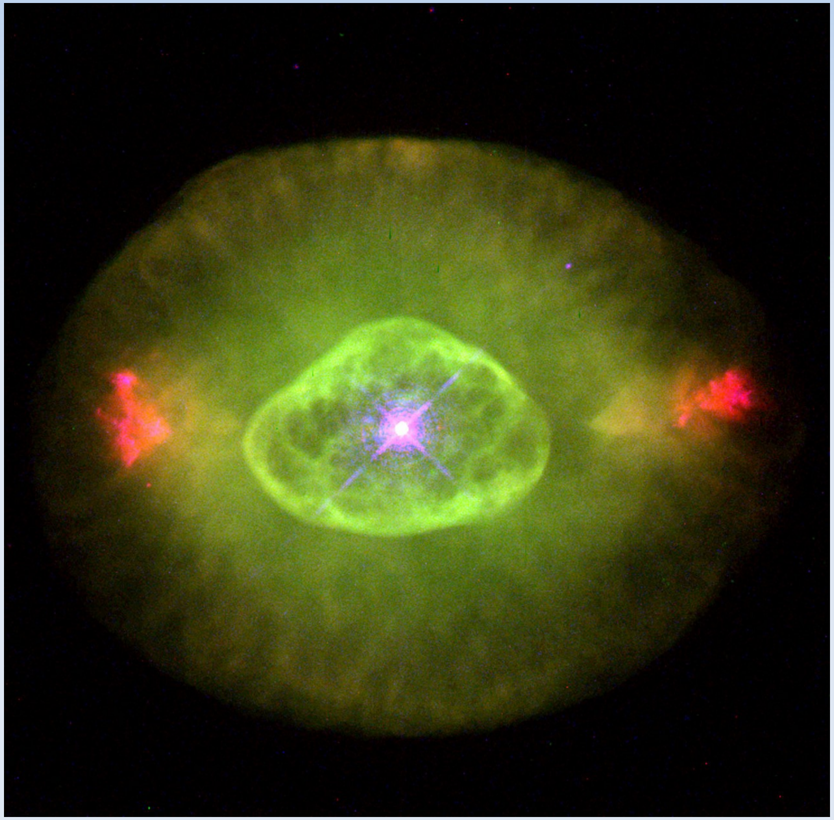
- Symbiotic binary
- Contains white dwarf and Mira star (variable red giant)
- Jet in optical and radio bands (Burgarella et al. 1992)
- Estimated jet age is ~100 years



[O III] 5007 intensity image of the R Aqr symmetrical jet shown as a contour plot (Hollis et al. 1998).

Examples: planetary nebulae

- FILIERS: fast low ionization features are observed in some planetary nebulae (e.g. Redman & Dyson, 1999)
- Interpreted as recombination zones behind supersonic fronts produced in mass loaded jets
- V~200-1000 km/s



NGC 6826

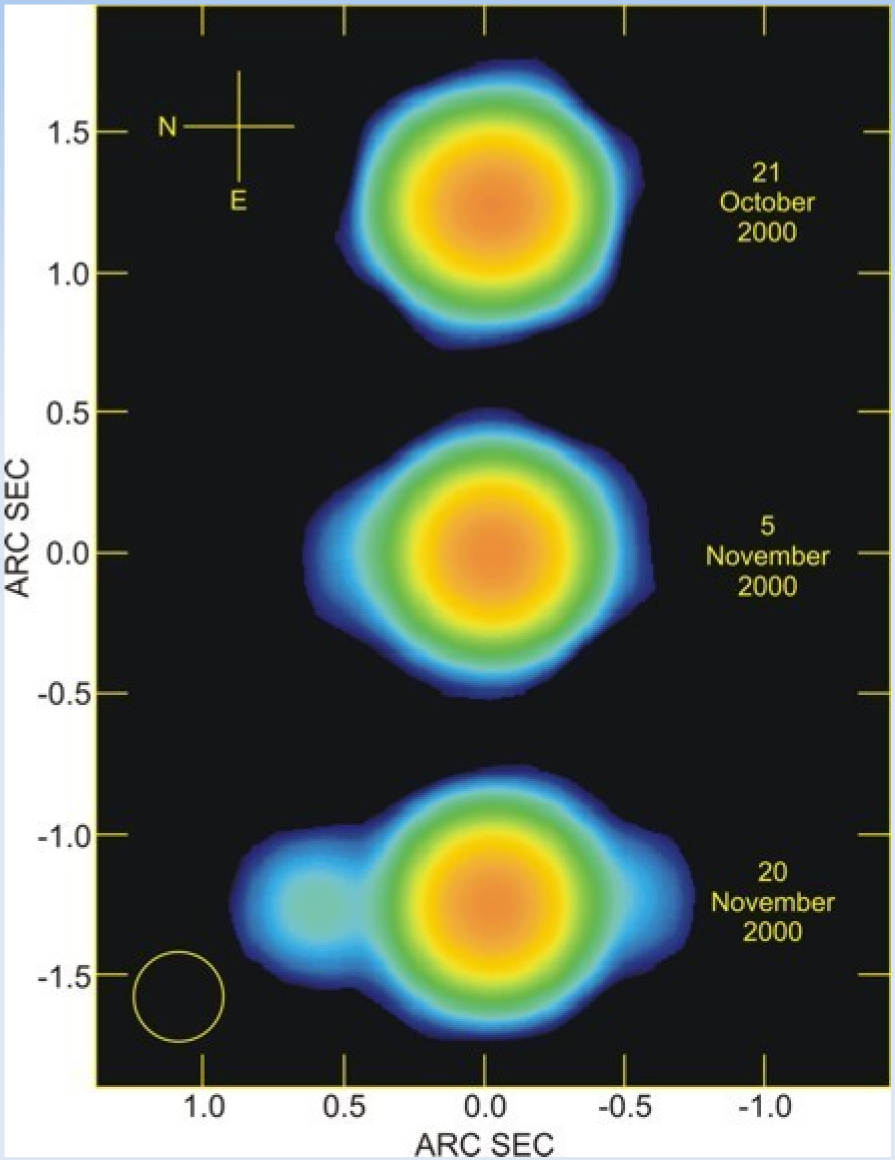
Example: Cir X-1

- Low mass X-ray binary with neutron star
- Very young NS (4600 yrs, in supernova remnant; ”bouncing baby”)
- Jet discovered in 2007
- The jet might be twisted and precessing (Coriat et al. 2019)

Chandra image

Examples: HMXB binaries

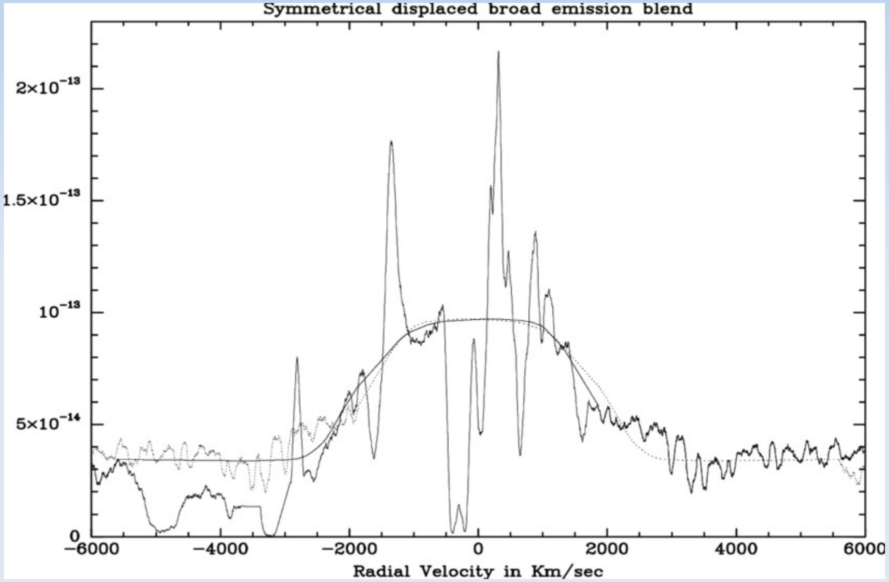
- Cyg X-3
- Contains compact star on 2.4 M_{sun} and Wolf-Rayet star
- Jet emitted at viewing angle about 14 deg (Koljonen et al. 2019)



(NRAO image)

Examples: supersoft X-ray sources

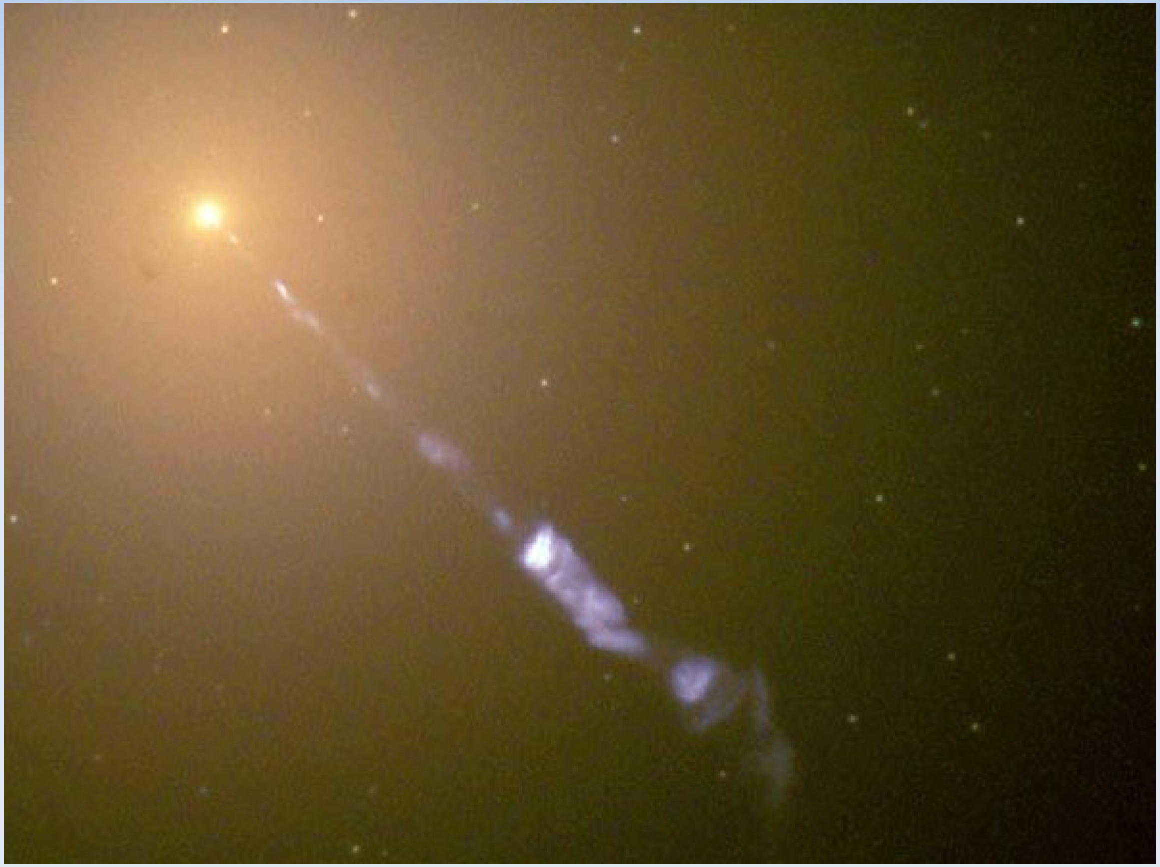
- RX J0513.9-6951
- Compact binary in Large Magellanic Cloud
- Accreting white dwarf; bb temperature 10^5 K, luminosity $L{\sim}10^{38}$ erg/s
- Discovered by ROSAT All sky survey
- Unusual emission lines, interpreted as high velocity bipolar outflows
- V~4000 km/s (Crampton et al. 1996)



Moving broad absorption feature near 1020A as possible O VI outflow associated with a precessing jet.

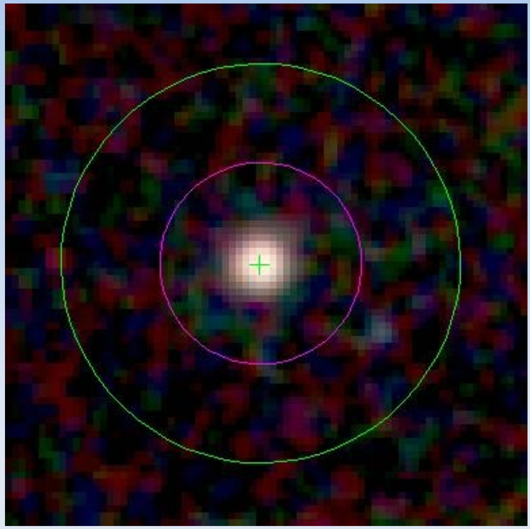
Examples: AGN

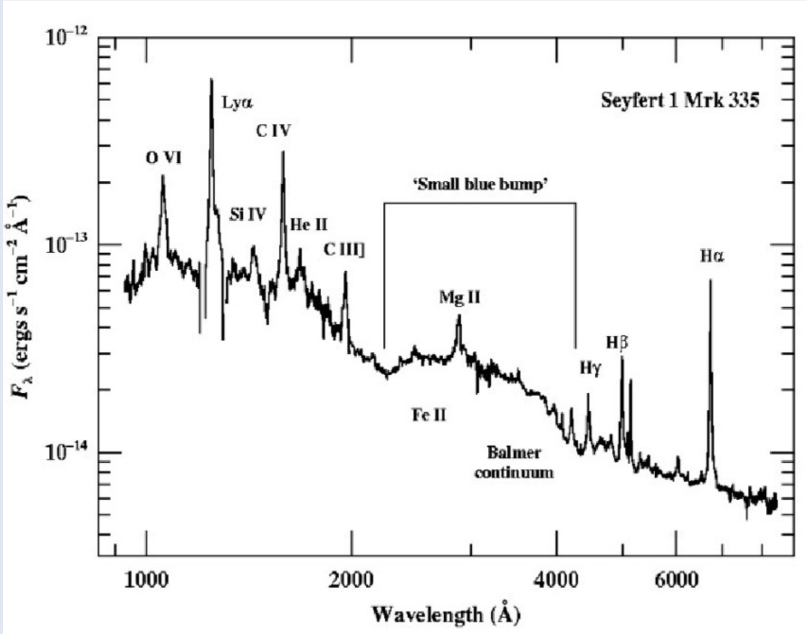
- M87
- Supergiant, elliptical galaxy
- Optical jet (HST image)
- Velocity of jet: gamma~3
- Large scale: 5000 light years



Active galactic nuclei

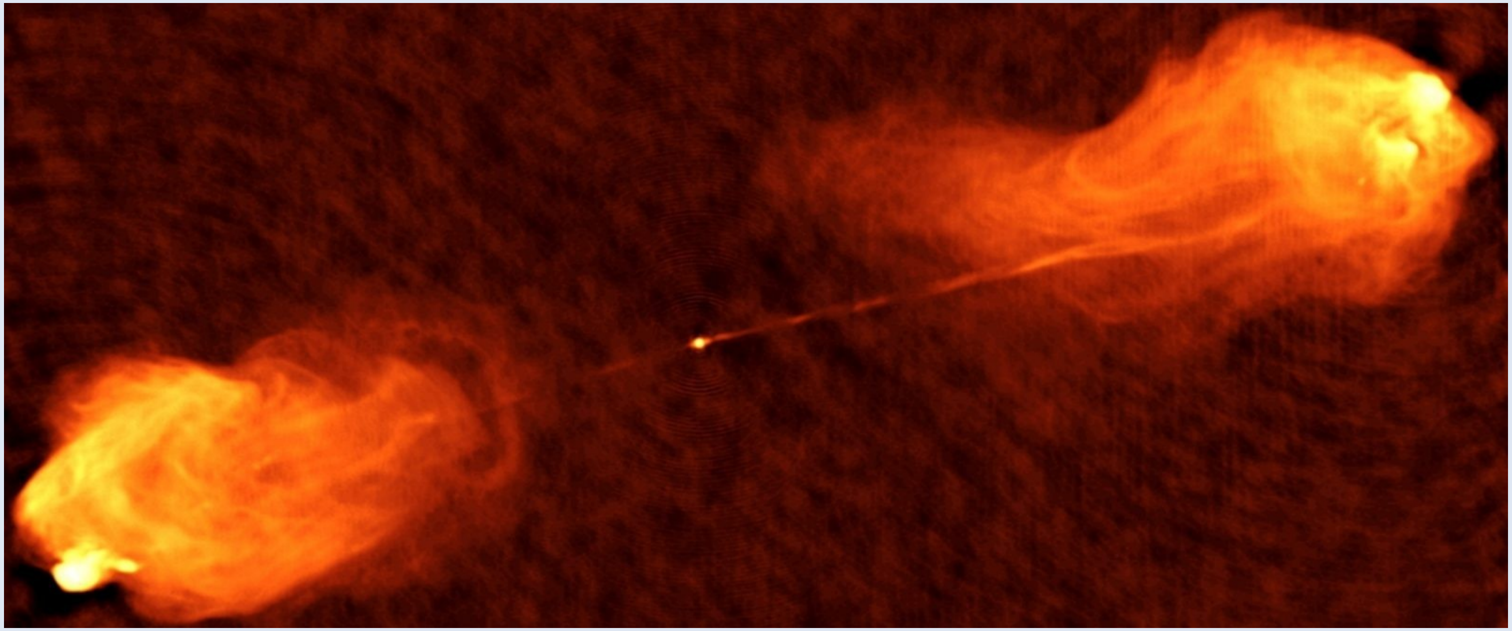
- An active galactic nucleus (AGN) is a compact region at the center of a galaxy that emits a significant amount of energy across the electromagnetic spectrum.
- The luminosity is not produced by stars. Such excess, non-stellar emissions have been observed in the radio, microwave, infrared, optical, ultra-violet, X-ray and gamma ray wavebands.
- A galaxy hosting an AGN is called an active galaxy.



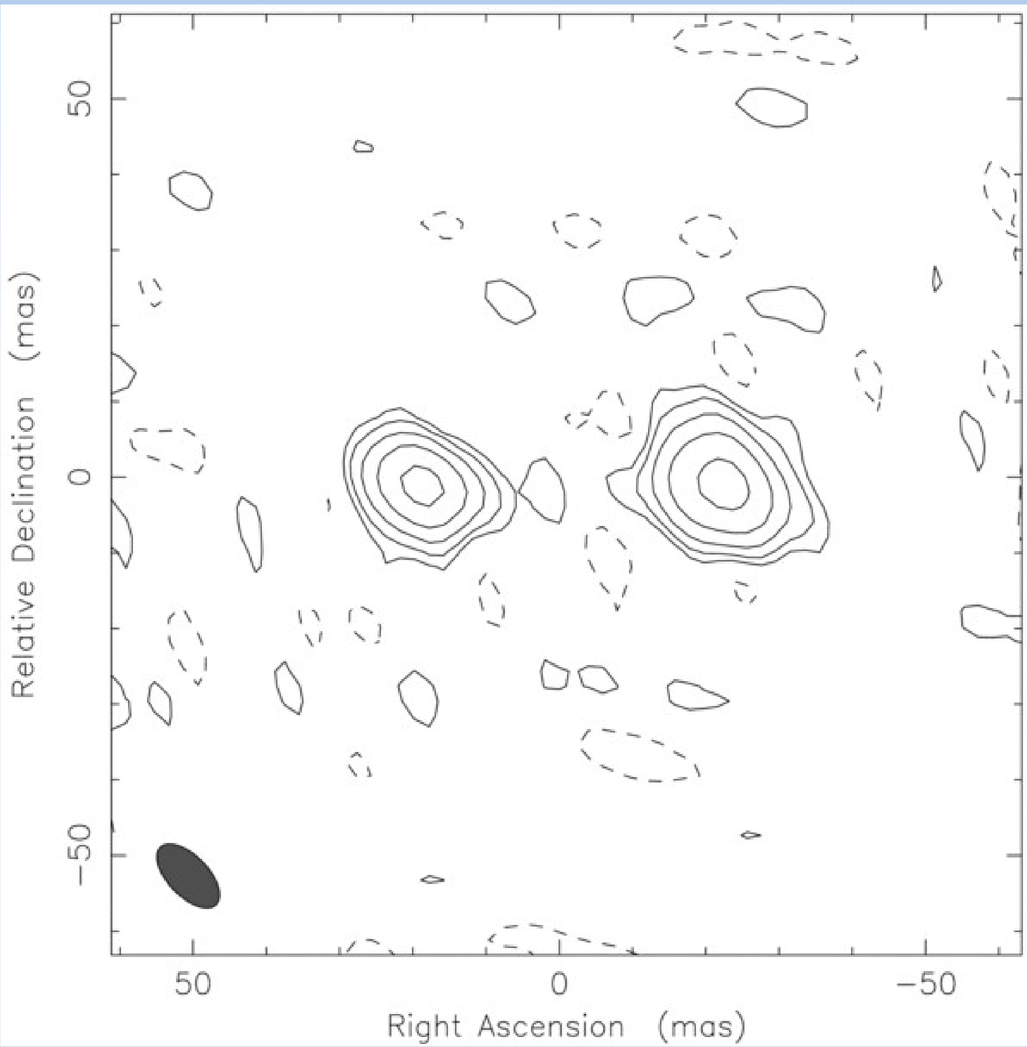


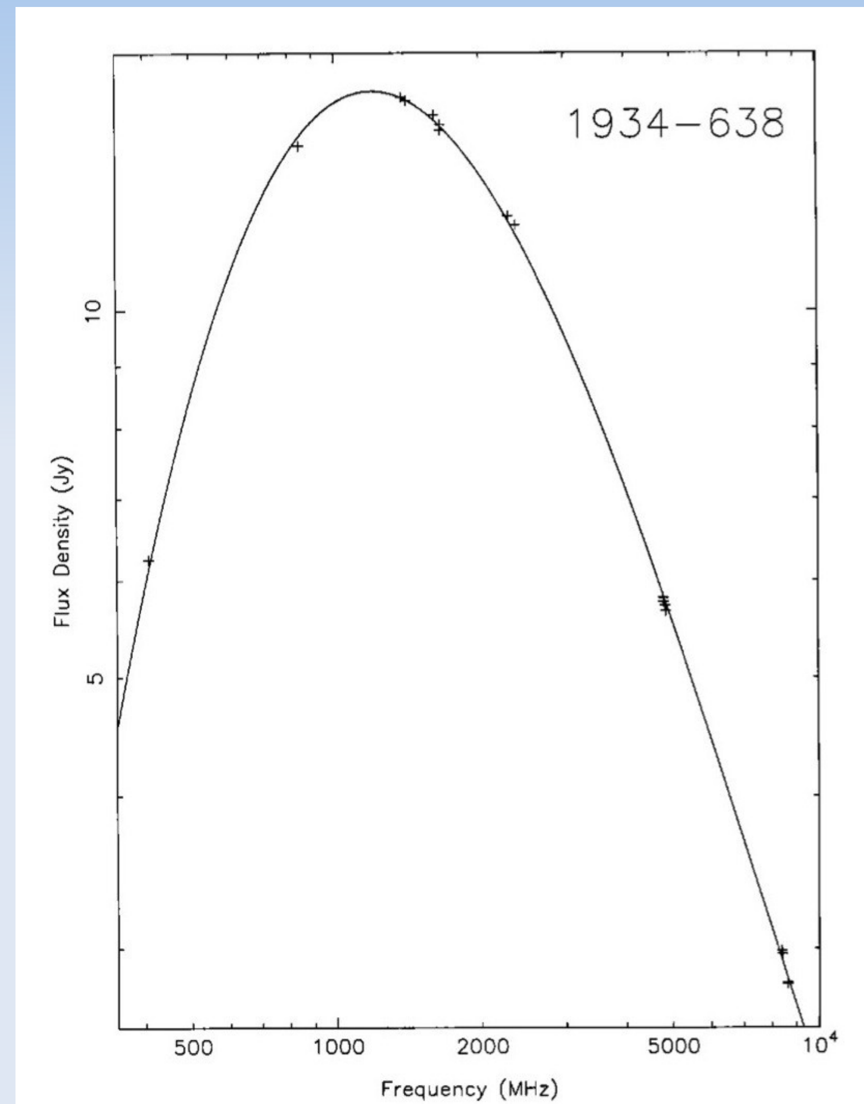
Examples: radiosources

- Jet velocity Gamma ~ 10
- Cygnus A: FR II type radiosource (Fanaroff-Riley), characteristic bright spots and faster motion of jets



GPS/CSS sources

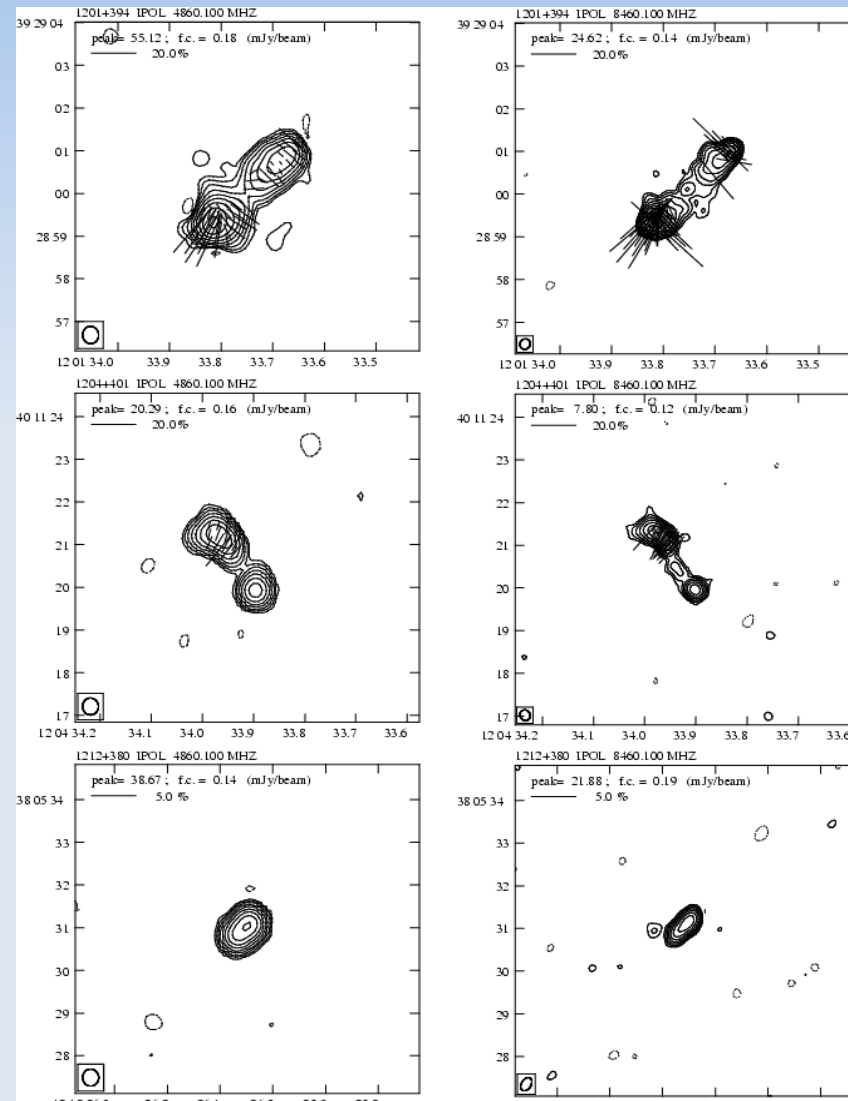




- PKS 1934-638

GPS radiosources

- Sources appear to be young, because they are compact
- Statistically, their young age would not match with the number of mature radioquasars
- This supports the hypothesis of reactivation



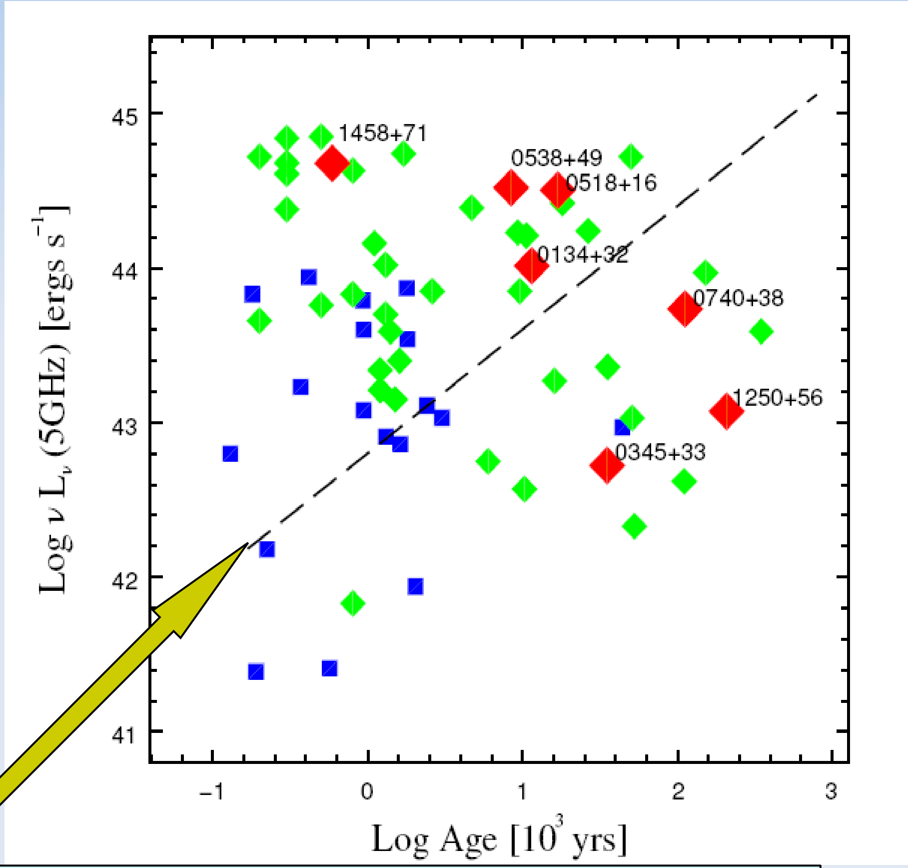
Fanti et al.; 2001

Radio sources: ageing estimates

- The sources are bright and have small size → their age is below 10^4 yrs.
- Observed statistical overabundance of the compact radio sources, in comparison with the large scale > 1kpc sources (O'Dea & Baum 1997)
- In fact they may be reactivating every 10^4 yrs (Reynolds & Begelman 1997)

GPS radiosources

- Giga-Hertz Peak Spectrum radioquasars
- Sample of 70 apparently young sources
- Hypothesis of reactivation due to the duty-cycle



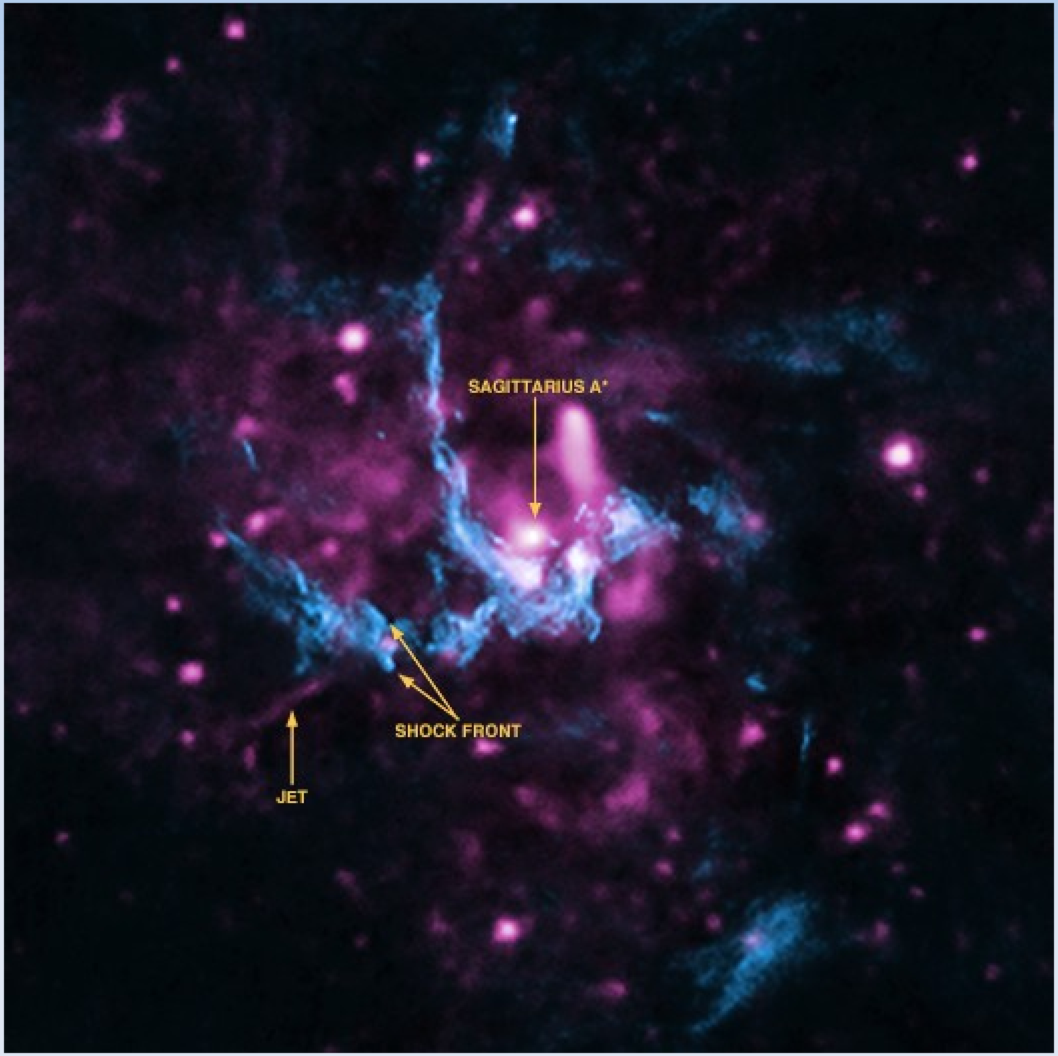
$$\log\left(\frac{T_{\rm burst}}{\rm yr}\right) \approx 1.25 \log\left(\frac{\nu L_\nu(5GHz)}{\rm erg/s}\right) + 0.38 \log\left(\frac{\alpha}{0.02}\right) + 1.25 \log K_{5GHz} - 53.6.$$

Czerny, Siemiginowska, Janiuk, Nikiel-Wroczyński, Stawarz; 2009, ApJ

Our Galaxy Center

Chandra image of Sgr A*

Does Sgr A* produce a jet?



Chandra X-ray image of the feature, given the name of G359.944-0.052 by its Galactic coordinates, exhibits a needle-shape.

Attributed to jet structure

(Z. Li, Morris, Baganoff, 2013, ApJ)

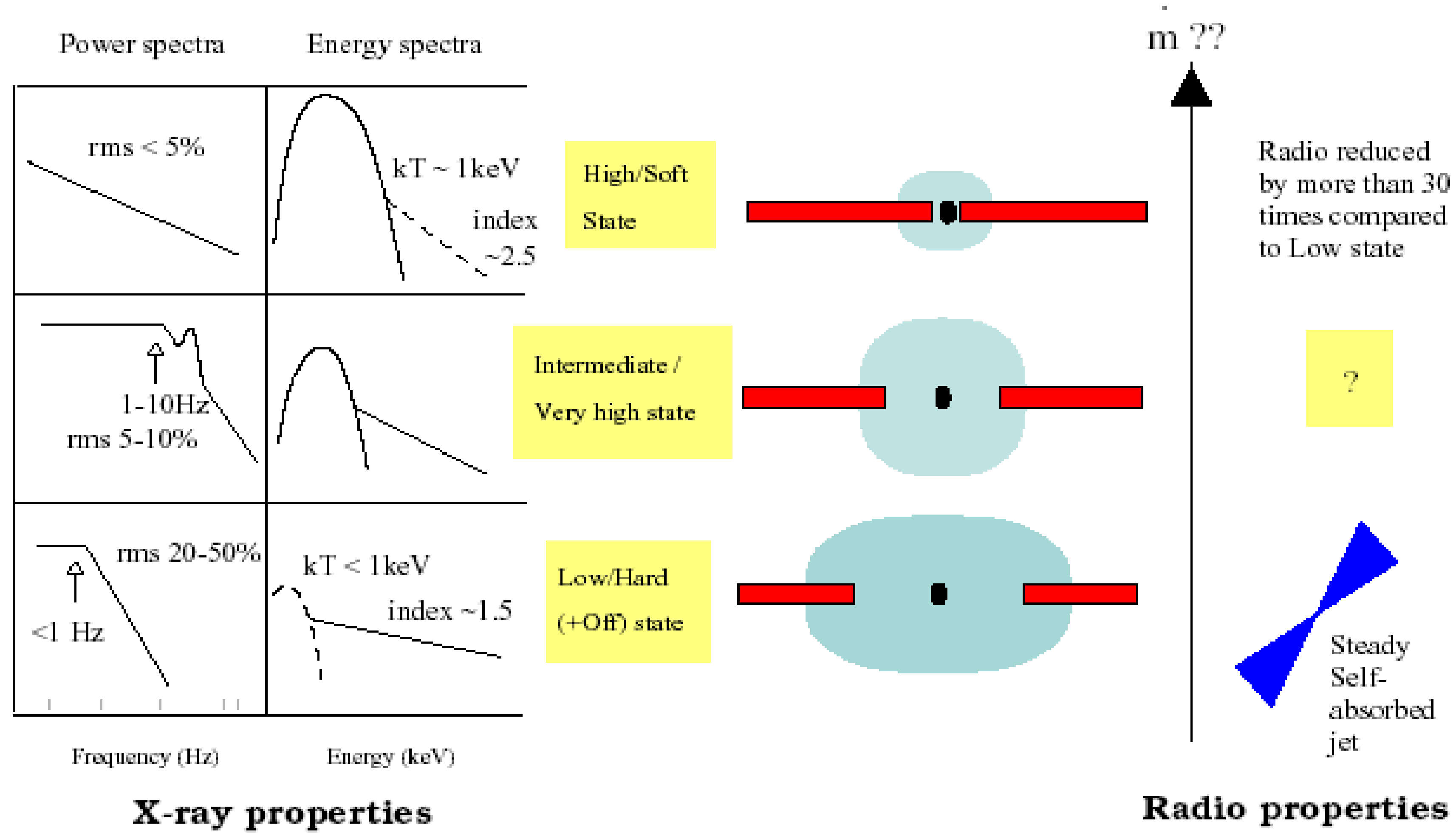
Origin of jets

- In all cases, the estimated jet velocity of order of escape velocity from the central object
- The jet must therefore be produced in the vicinity of the central object, at inner regions of an accretion disk
- In microquasars, observed correspondence between the X-ray, IR and Radio fluxes and constant time delay suggest that the inner disk ejects the plasma, responsible then for IR and Radio flares by synchrotron emission (e.g. Fender et al. 1997)

Advection Dominated Accretion (ADAF)

- Infalling (or accreting) matter falls into a black hole without radiating away much of its energy, less than one percent.
- Density of the infalling matter is low, so the particles make few collisions or their way beyond the event horizon.
- If the matter is falling onto a neutron star, or is spiralling slowly in a thick disk toward a black hole, it can radiate away ten to a hundred times more energy than in the advection case.

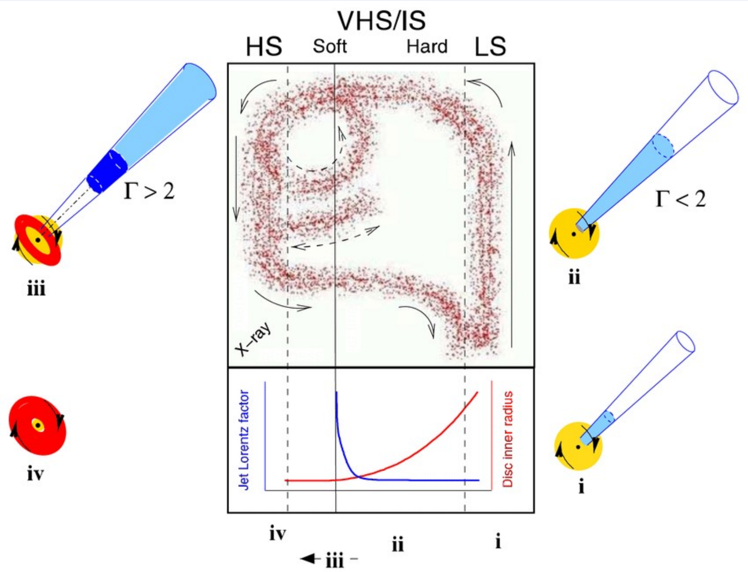
Phenomenology: X-ray - radio



Fender 2000

ADAF and jets

- Radio emission is too bright to be produced by thermal electrons on the accretion flow
- It may come from nonthermal electrons in a jet
- Radio jets are observed in hard states of the XRB
- Optically thin ADAF might be associated with jet production, in low luminosity states



Established pattern:

- LS → steady jet
- HS → no jet
- VHS → transient jet

Fender et al. (2005)

Various accretion solutions

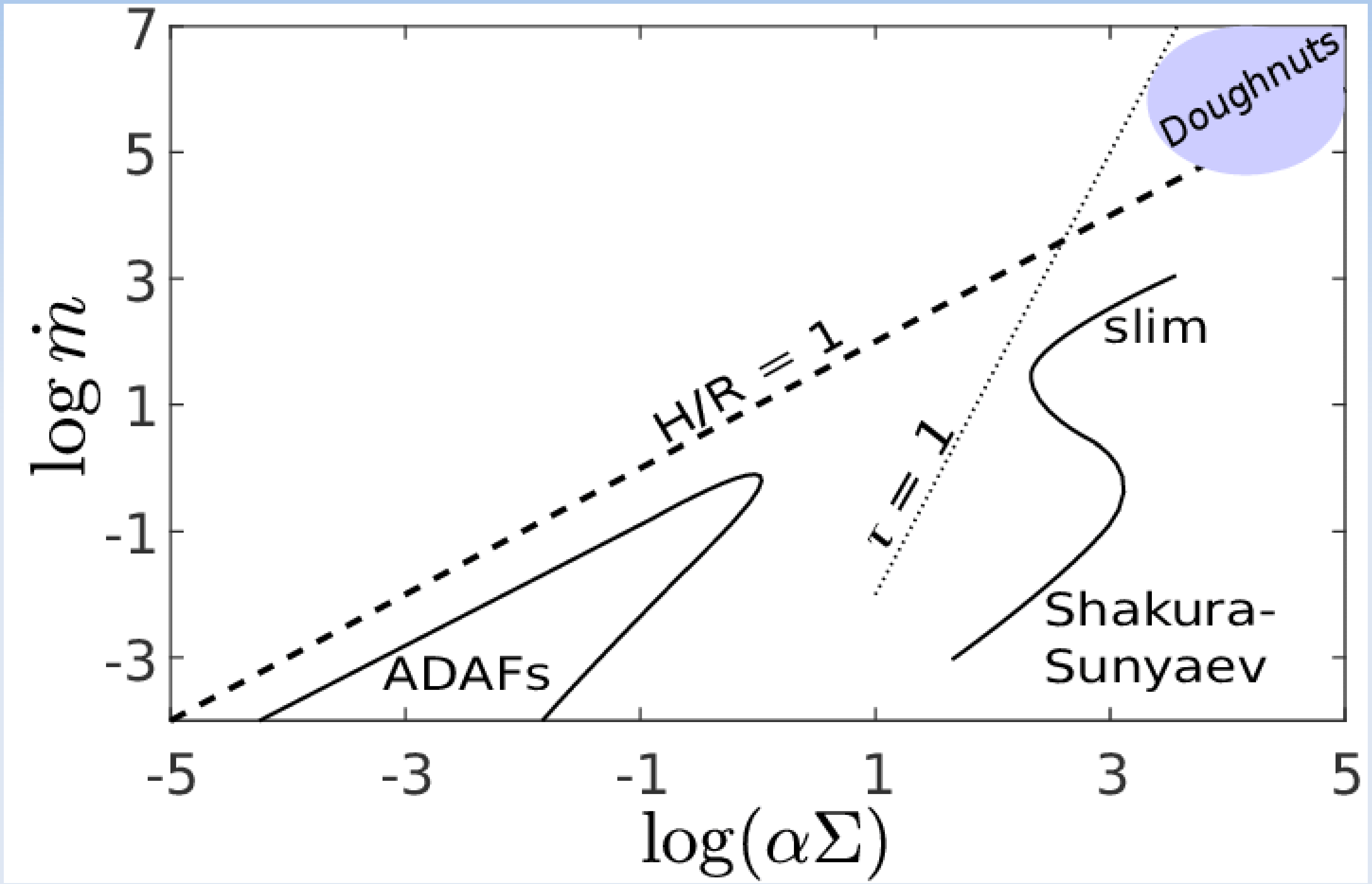


Figure adopted (with some simplifications) from Lasota (2015), the original appeared in Abramowicz et al. (1995).

ADAF branch: developed by Narayan & Yi (1994), cf Yuan (2001)

One-dimensional equations

mass $$\frac{d}{dR}(\rho R H v) = 0,$$

mom. $$v\frac{dv}{dR} - \Omega^2 R = -\Omega_K^2 R - \frac{1}{\rho}\frac{d}{dR}(\rho c_s^2),$$

ang. mom. $$v\,\frac{d(\Omega R^2)}{dR} = \frac{1}{\rho R H}\frac{d}{dR}\left(\nu \rho R^3 H \frac{d\Omega}{dR}\right)$$

energy One-T: (internal E, P term, viscosity heating, radiation cooling)

$$\rho v\left(\frac{de}{dR} - \frac{p}{\rho^2}\frac{d\rho}{dR}\right) = \rho \nu R^2\left(\frac{d\Omega}{dR}\right)^2 - q^-,$$

Two-T: (viscous heating, collision loss)

$$q^{\rm adv,i} \equiv \rho v\left(\frac{de_i}{dR} - \frac{p_i}{\rho^2}\frac{d\rho}{dR}\right) \equiv \rho v\frac{de_i}{dR} - q^{i,c} = (1-\delta)q^+ - q^{\rm ie},$$

$$q^{\rm adv,e} \equiv \rho v\left(\frac{de_e}{dR} - \frac{p_e}{\rho^2}\frac{d\rho}{dR}\right) \equiv \rho v\frac{de_e}{dR} - q^{e,c} = \delta q^+ + q^{\rm ie} - q^-.$$

(viscous heating, collision gain, radiation loss)

(delta: % of viscous heating that goes to e^-, unknown, depend on microphysics)

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Main features

- Large radial velocity:

$$v_r \sim \frac{\alpha c_s H}{R}$$

C_s=(P/rou)^0.5

- Sub-Keplerian rotation: pressure-gradient support
- High temperature: $T \sim \frac{GMm_p}{6kR} \sim \frac{10^{12}}{r}$ (Virial)
- Geometrically thick: $(H = \frac{c_s}{\Omega_k} \sim R)$ ~spherical
- Optically thin (because of large radial velocity)
- Two-temperature: $T_i \gg T_e$
  - coupling between ions and electrons not strong enough
  - plasma collective behavior also too weak

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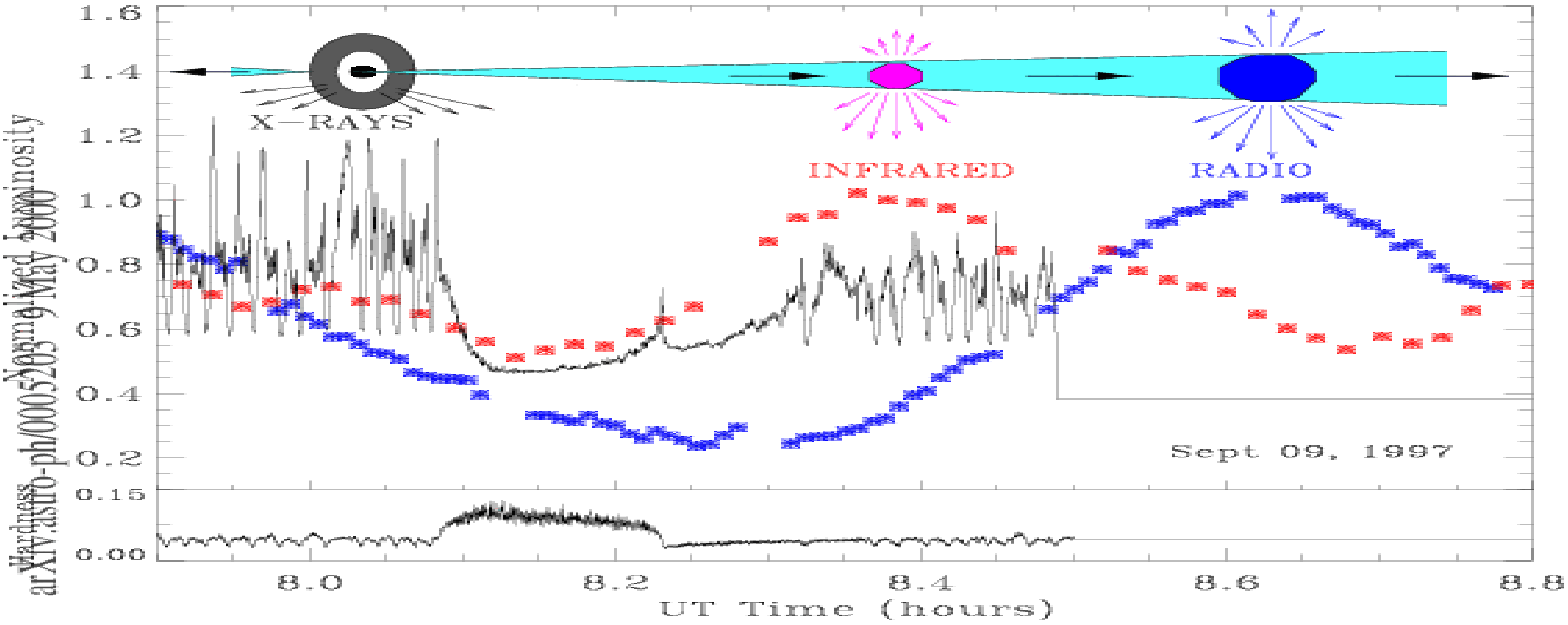
Jet-disk connection



Ejection of radio jets are preceeded by enhanced X-ray activity.

The jet presence may be related to the accretion disk activity.

Jet-disk connection

- **Is the accretion disk required to produce jets? Probably yes. Collimation is less certain.**
  - For YSO, XRBs, SSS there if a firm observational evidence for the disks' presence
  - For AGNs, the evidence is sometimes far less obvious (emission lines, dusty tori, sub-parsec molecular disks)
  - For PNe, mainly speculative/theoretical arguments for disk presence (Livio & Pringle 1996)
- **Is the jets/outflows required to remove angular momentum from disk?**
  - For some AGN, the MHD driven jets are suggested (observed rotation in winds; but also precession possible)
  - For CVs, the angular momentum is transported in the disk and outer radius expands, wind is not required

What may help driving the jet

- **Central object fast rotation (near break up)**
- **Compactness of the star: determines the escape velocity and so the jet speed**
- High luminosity: radiation pressure driven winds (Proga & Drew 1997)
- Funnel (ADAF flow in AGNs or slow winds in Planetary Nebulae) may provide a collimation
- Boundary layer od NS (?)

Next week

- More about jets physics in general
- How to launch jet from black hole horizon. Blandford Znajek and Penrose processes.

- Morphology of large scale jets from AGN
- Blazars, QSOs, Seyferts: unification scheme

Further reading: R. Fender, ”Jets from X-ray binaries”, (review), 2006, in: Compact Stellar X-ray sources **arXiv:astro-ph/0303339**