Friedrich–Alexander–Universität
Erlangen–Nürnberg

ERLANGEN CENTRE
FOR ASTROPARTICLE
PHYSICS

Multi-Wavelength Astronomy

Jörn Wilms, Matthias Kadler

`http://pulsar.sternwarte.uni-erlangen.de/wilms/teach/multiwave/`

Sommersemester 2009

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Introduction

Schedule

Introduction			
20.04.	JW	Introduction, Historical	AGN classes
27.04.	JW	Radiative Processes	Broad Band Spectra
04.05.	JW	Measurements and Statistics	
Radio Astronomy			
11.05.	MK	Radio Antennas	21 cm and masers
18.05.	MK	Radio Interferometry	Jets
25.05.	MK	Radio Interferometry	Jets
01.06.	no lecture (pentacost)		
Optical Astronomy			
08.06.	JW	Optical Telescopes	LSST et al.
15.06.	JW	CCDs, IR Detectors	IR surveys
High Energy Astronomy			
22.06.	JW	High Energy Detectors	X-ray spectra
29.06.	no lecture (conferences)		
Multi-wavelength Campaigns			
06.07.	MK	Multi Wavelength Campaigns, I	AGN variability
13.07.	MK	Multi Wavelength Campaigns, II	AGN variability
20.07.	JW, MK	Buffer	

Literature

BRADT, H., 2004, *Astronomy Methods: A Physical Approach to Astronomical Observations*, Cambridge: Cambridge Univ. Press, $50

Good general overview book on astronomical observations at all wavelengths.

BRADT, H., 2008, *Astrophysics Processes: The Physics of Astronomical Phenomena*, Cambridge: Cambridge Univ. Press, 48€

Good general overview book on the physics of astronomically relevant processes at all wavelengths.

LONGAIR, M.S., 1992, *High Energy Astrophysics, Vol. 1: Particles, Photons, and their Detection*, Cambridge: Cambridge Univ. Press, ∼50€

Good introduction to high energy astrophysics, the 1st volume deals extensively with high energy procsses, the 2nd with stars and the Galaxy. The announced 3rd volume has never appeared. Unfortunately, everything is in SI units.

Literature

KITCHIN, C.R., 2008, *Astrophysical Techniques*, 5th edition, IoP, 58€

Overview over most detection techniques used in astronomy.

KNOLL, G.F., 2000, *Radiation Detection and Measurement*, 3rd edition, New York: Wiley, 126€

The bible on radiation detection. If you want one book on detectors, this is it.

BURKE, B.F. & GRAHAM-SMITH, F., 2002, *An Introduction to Radio Astronomy*, 2nd edition, Cambridge Univ. Press, 49€

General introduction to radio astronomy, explaining both the techniques used and the major observational results.

“Adorant” (Geissenklösterle cave near Blaubeuren (Lkr. Ulm; 3.8 cm × 1.4 cm, Age 36000 years, Original: Landesmuseum Stuttgart).
Figure: Constellation? Holes: lunar calendar?

Sky Disk of Nebra (bronze age, ⌀ 32 cm, fabricated 2100–1700 BC)

Astronomical observations go back a long time.

History of Multiwavelength Astronomy

Tycho Brahe (1546–1601; Hven Island): visual determination of planetary positions with precision not reached before Tycho.

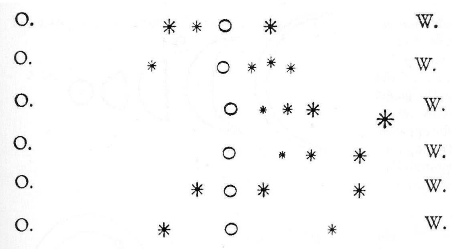
⟹ shows errors in predictions based on old ptolemaic system

(order of magnitude: some arc minutes)

Brahe, Astronomiae Instauratae Mechanica, 1598

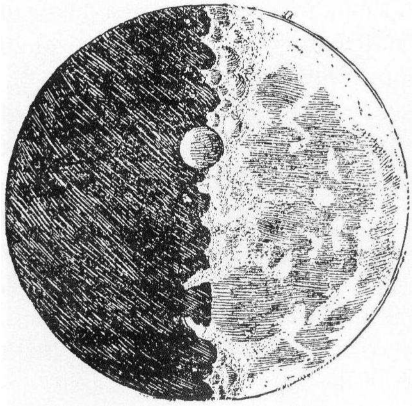
IMSS Florenz

Galileo Galilei (1564–1642):
25.08.1609: Telescope as an astronomical instrument
⟹ Observations!



Galileo Galilei (1564–1642):
25.08.1609: Telescope as an astronomical instrument
⟹ Observations!

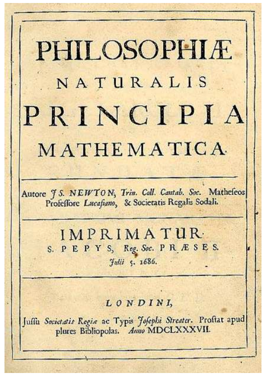
Siderius Nuncius (1610): Jupiter's Moons



Galileo Galilei (1564–1642):
25.08.1609: Telescope as an astronomical instrument
⟹ Observations!

Siderius Nuncius (1610): Moon

Isaac Newton (1642–1727)



PHILOSOPHIÆ
NATURALIS
PRINCIPIA
MATHEMATICA.

Autore J S. NEWTON, Trin. Coll. Cantab. Soc. Matheseos Professore Lucasiano, & Societatis Regalis Sodali.

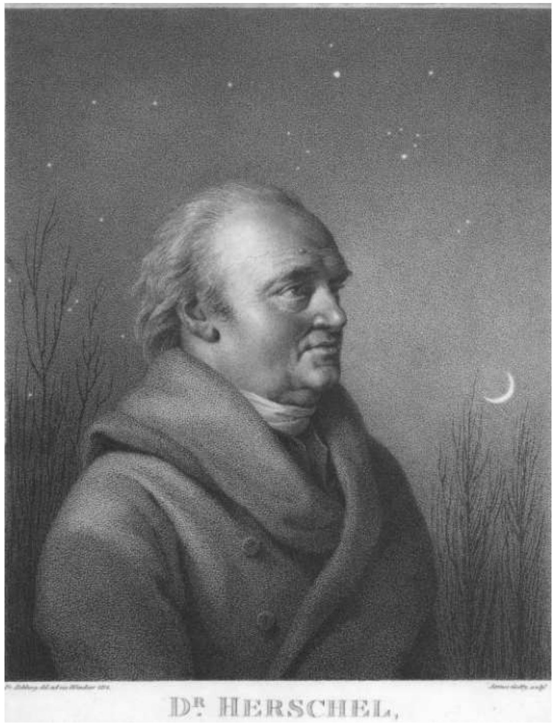
IMPRIMATUR.
S. PEPYS, Reg. Soc. PRÆSES.
Julii 5. 1686.

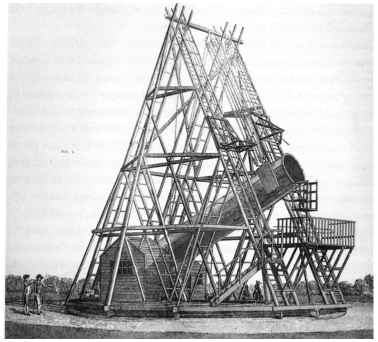
LONDINI,
Jussu Societatis Regiæ ac Typis Josephi Streater. Prostat apud plures Bibliopolas. Anno MDCLXXXVII.

Principia (1687): Gravitation as cause for planetary motion

$$F = G\,\frac{M_1 M_2}{r^2}$$

Begin of modern, physics based astronomy ("Astrophysics").





William Herschel (1738–1822):

- 15.11.1738: born Hannover, Oboist
- 1759: Emigration to England
- 13.03.1781: Discovery of Uranus
- Measurement of stellar positions (together with Caroline Herschel), Shape of the Galaxy

Friedrich Wilhelm Bessel (1784–1846):

19. Century: Astronomy develops as a modern science:

- precise positions (“Durchmusterungen”)
- photography
- spectroscopy (real Astro*physics*)

Bessel (1839): first measurement of the distance of a star

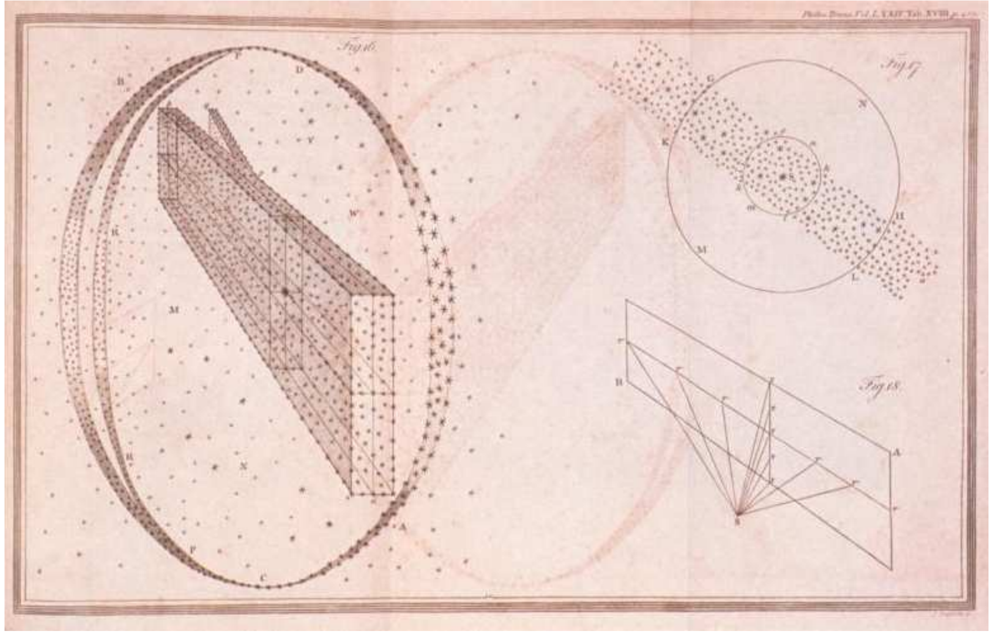
ASTRONOMISCHE NACHRICHTEN.
№. 365. 366.

Bestimmung der Entfernung des 61sten Sterns des Schwans.
Von Herrn Geheimen-Rath und Ritter *Bessel*.

Als es *Bradley* gelungen war, seine Beobachtungen in *Kew* und *Wansted*, welche die Entdeckungen der Aberration und Nutation herbeiführten, durch diese allein genügend zu erklären, ohne dazu der Annahme einer jährlichen Parallaxe der beob-

ist nicht zu bezweifeln; allein wenn eine Untersuchung über die jährliche Parallaxe eines Fixsterns unternommen werden soll, so sind sie dennoch die einzigen, welche seine Wahl leiten können.

61 Cyg: parallax is $0.3''$
⟹ distance 11 light years



Geometry of the Milky Way after William Herschel (1785)

Albert Einstein (1879–1955): New concepts of space and timeZeit.

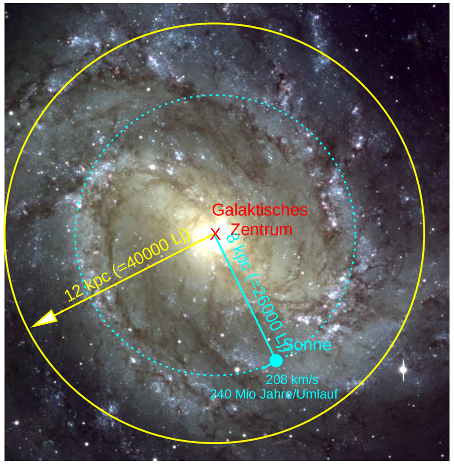
c constant in all coordinate systems
⟹ special relativity (1905)

presence of matter leads to curvature of space (=Gravitation)
⟹ general theory of relativity (1915)

relativity also applicable for universe as a whole

Mt. Palomar 5 m Telescope

Henrietta Leavitt (1868–1921)

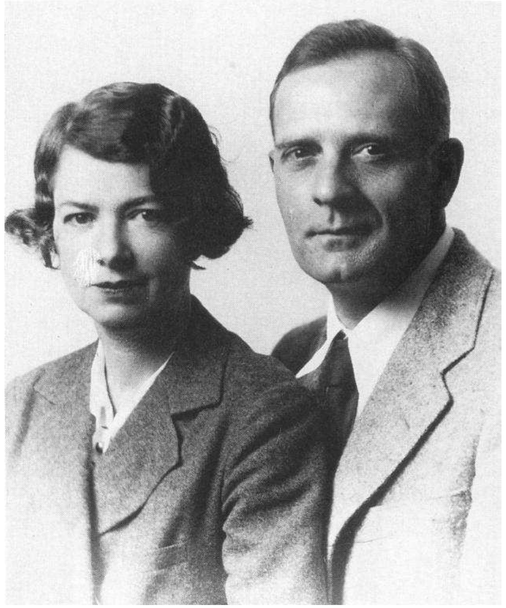


Early 20. century:

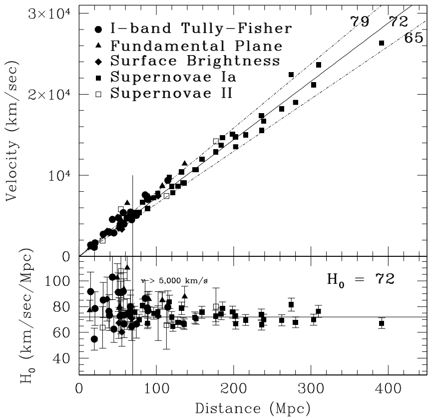
- large telescopes (Mt. Wilson [2.5 m], Palomar [5 m]),
- Astronomy of “nebulae”:

$\Longrightarrow$ systematic studies of structure of Galaxy,

$\Longrightarrow$ distance determination



Edwin Hubble (1889–1953)

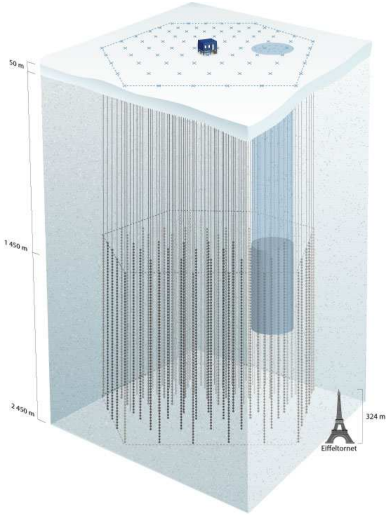


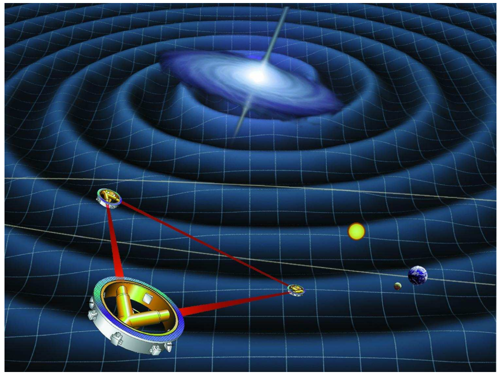
- The Universe expands
- Galaxies are other Milky Ways

after WW2: multi-wavelength astronomy

- 1950ff.: radio astronomy
- 1950ff.: infra red astronomy
- 1960ff.: X-ray and Gamma-Ray Astronomy
- 1970ff.: Astronomy with satellites
- 2000ff.: TeV-Astronomy

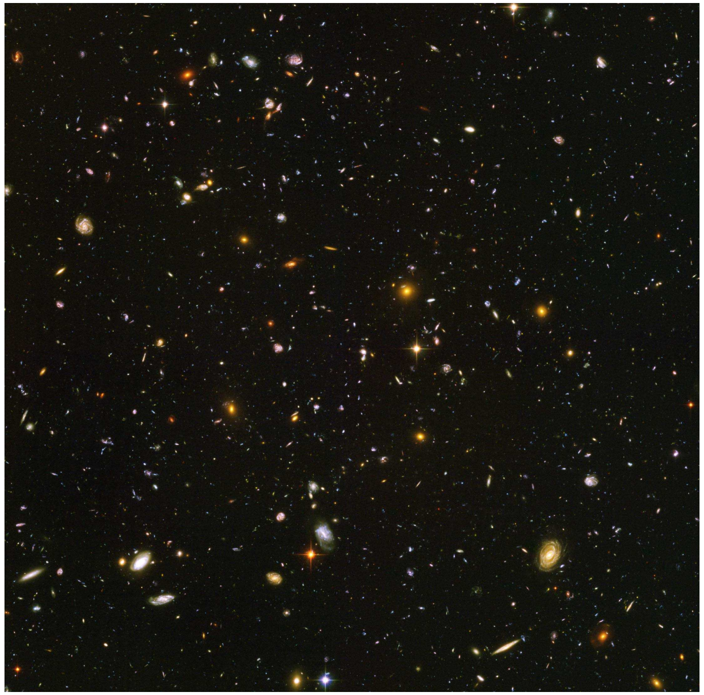
$\Longrightarrow$ Astronomy = international large scale research in physics



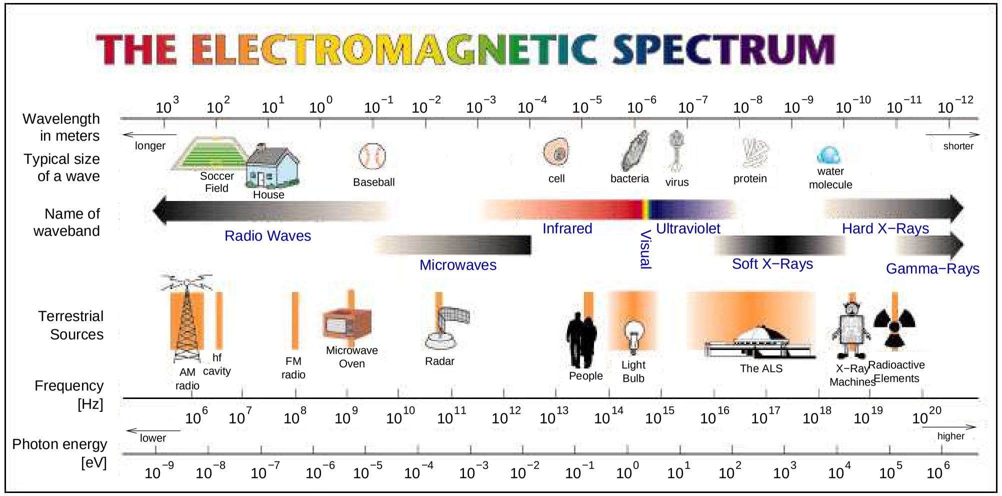


Seit ~2000: “Multi-Messenger Astronomy”:

- (1910/1911 (V. Hess): cosmic rays)
- 2015ff.: astronomy with neutrinos
- 2025ff.: LISA: gravitational wave astronomy



Why Multi-Wavelength Astronomy?



Electromagnetic Spectrum

As we all know, light can be characterized by

Wavelength: λ, measured in m, mm, cm, nm, Å.

Frequency: ν, measured in Hz, MHz.

Energy: E, measured in J, erg, Rydbergs, eV, keV, MeV, GeV.

Temperature: T, measured in K.

These quantities are related:

$$\lambda\nu = c \qquad E = h\nu \qquad T = E/k \tag{3.1}$$

where

$$c = 299792458\,\mathrm{m\,s^{-1}} \qquad \sim 2.998\times10^{10}\,\mathrm{cm\,s^{-1}} \tag{3.2}$$

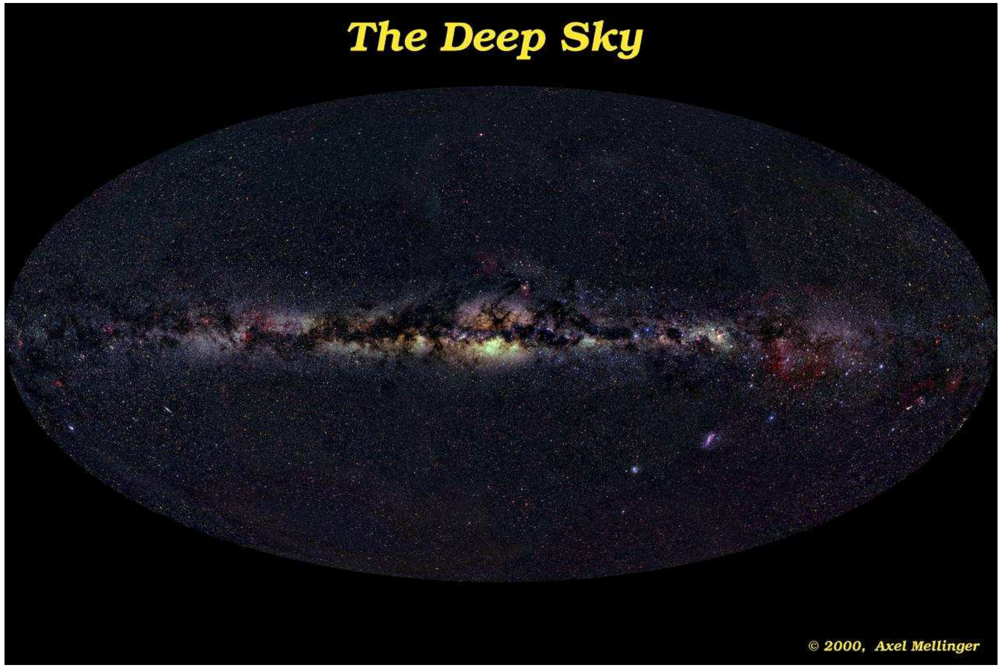
$$h = 6.6260693(11)\times10^{-34}\,\mathrm{J\,s} \qquad \sim 6.626\times10^{-27}\,\mathrm{erg\,s} \tag{3.3}$$

$$k = 1.3806505(24)\times10^{-23}\,\mathrm{J\,K^{-1}} \qquad \sim 1.38\times10^{-16}\,\mathrm{erg\,K^{-1}} \tag{3.4}$$

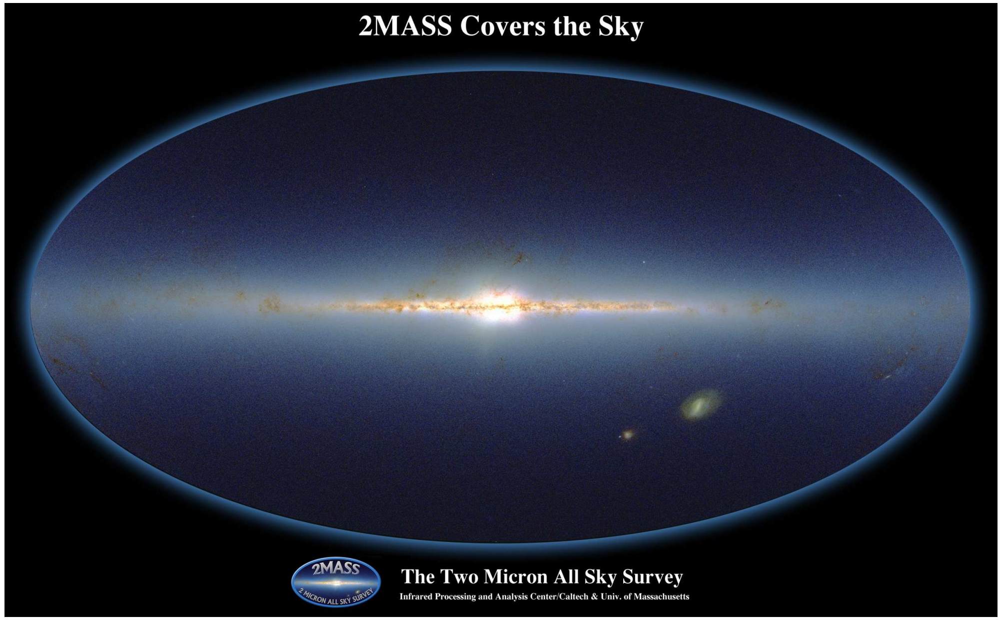
Constants are 2002 CODATA values, `http://physics.nist.gov/cuu/Constants/index.html` uncertainty is 1σ in units of last digit shown.

Conversion table (courtesy Eureka Scientific, `www.eurekasci.com`):

From $\Downarrow$ To $\Longrightarrow$	λ[Å]	$\lambda[\mu\text{m}]$	λ[cm]	ν[Hz]	E[keV]	E[erg]
λ[Å]	1	$10^{-4}\lambda$	$10^{-8}\lambda$	$3\times10^{18}/\lambda$	$12.4/\lambda$	$2\times10^{-8}/\lambda$
$\lambda[\mu\text{m}]$	$10^{4}\lambda$	1	$10^{-4}\lambda$	$3\times10^{14}/\lambda$	$1.24\times10^{-3}/\lambda$	$2\times10^{-12}/\lambda$
λ[cm]	$10^{8}\lambda$	$10^{4}\lambda$	1	$3\times10^{10}/\lambda$	$1.24\times10^{-7}/\lambda$	$2\times10^{-16}/\lambda$
ν[Hz]	$3\times10^{18}/\nu$	$3\times10^{14}/\nu$	$3\times10^{10}/\nu$	1	$4.14\times10^{-18}\nu$	$6.63\times10^{-27}\nu$
E[keV]	$12.4/E$	$1.24\times10^{-3}/E$	$1.24\times10^{-7}/E$	$2.42\times10^{17}E$	1	$1.60\times10^{-9}E$
E[erg]	$2\times10^{-8}/E$	$2\times10^{-12}/E$	$2\times10^{-16}/E$	$1.51\times10^{26}E$	$6.24\times10^{8}E$	1



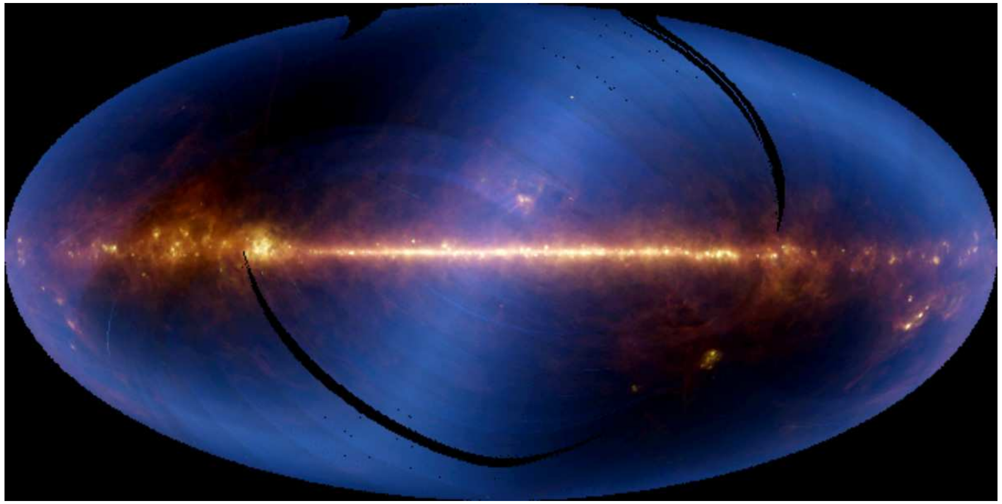
Milky Way in Optical



Infra red: Dust becomes transparent!

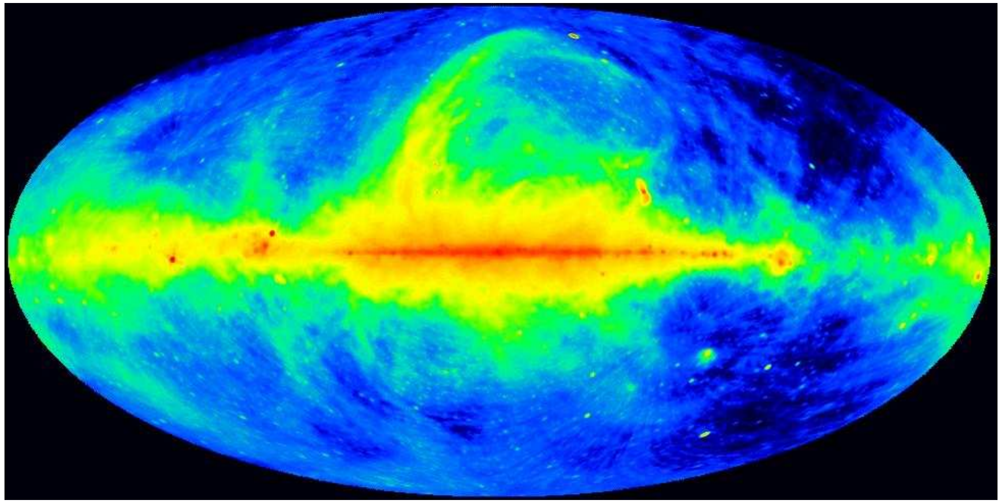
2MASS: 3 IR Bands: J (1.25 μm), H (1.65 μm), K$_s$ (2.17μm)

Milky Way in Near Infra Red



Milky Way in far Infra Red

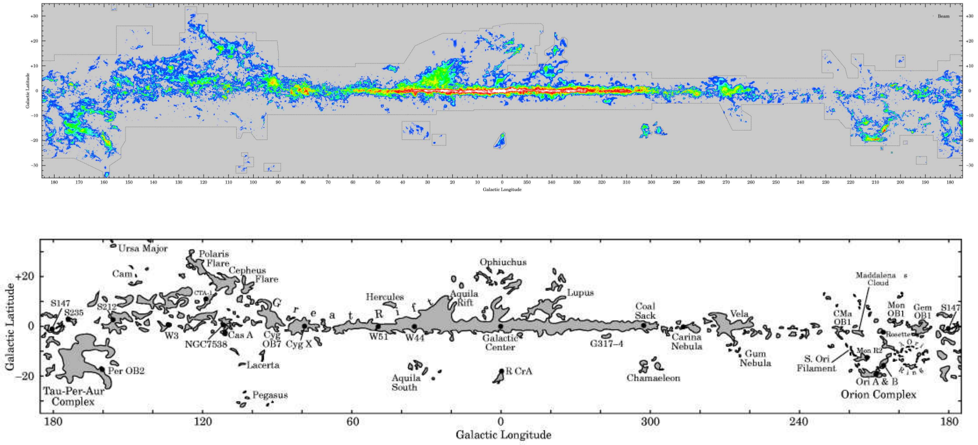
IRAS: 3 IR Bands: blue (12 μm), green (60 μm), red (100 μm)



G.T. Haslam et al., MPI für Radioastronomie 1982

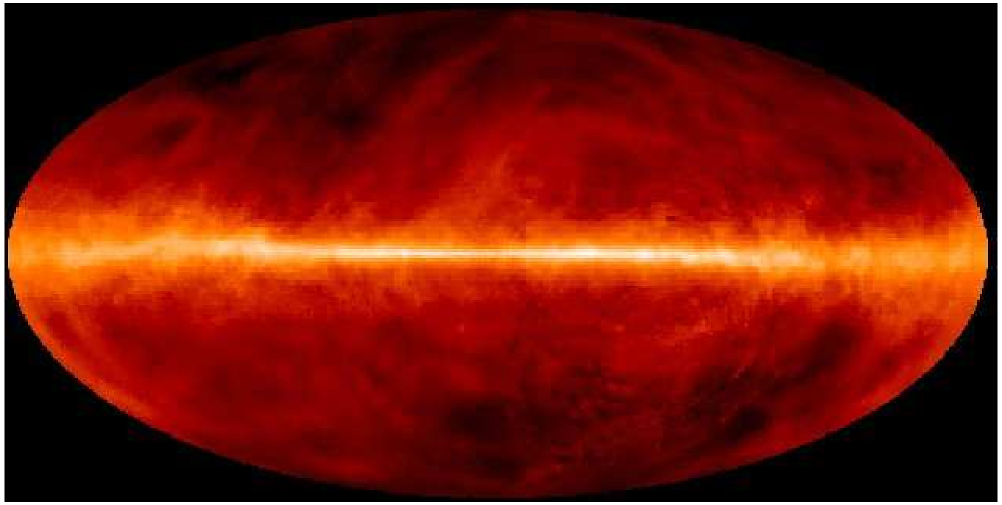
Milky Way in radio ($\lambda = 73\,\text{cm}$, $\nu = 408\,MHz$)

Continuum radiation (bremsstrahlung, synchrotron radiation)



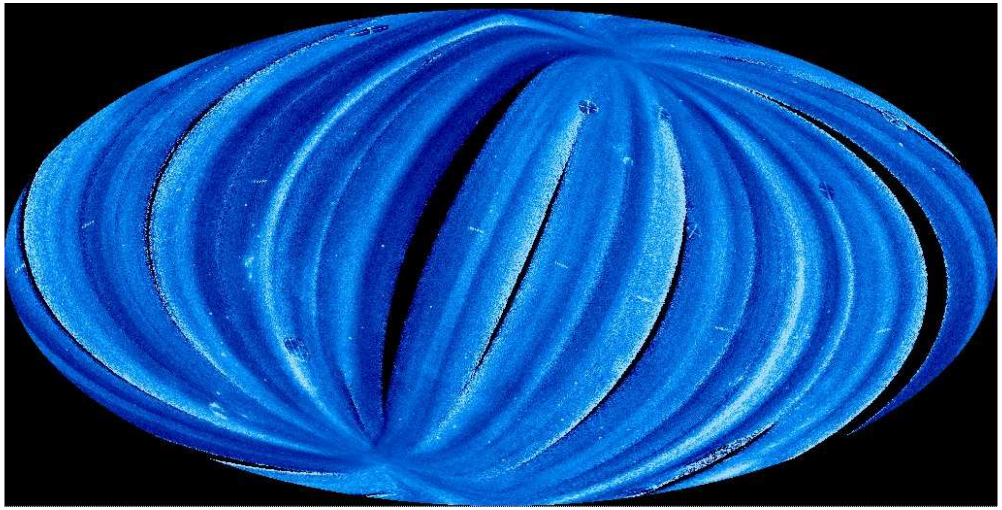
(Dame, Hartmann & Thaddeus, 2001, Fig. 2)

Distribution of CO molecules (1–0 line at 115 GHz)



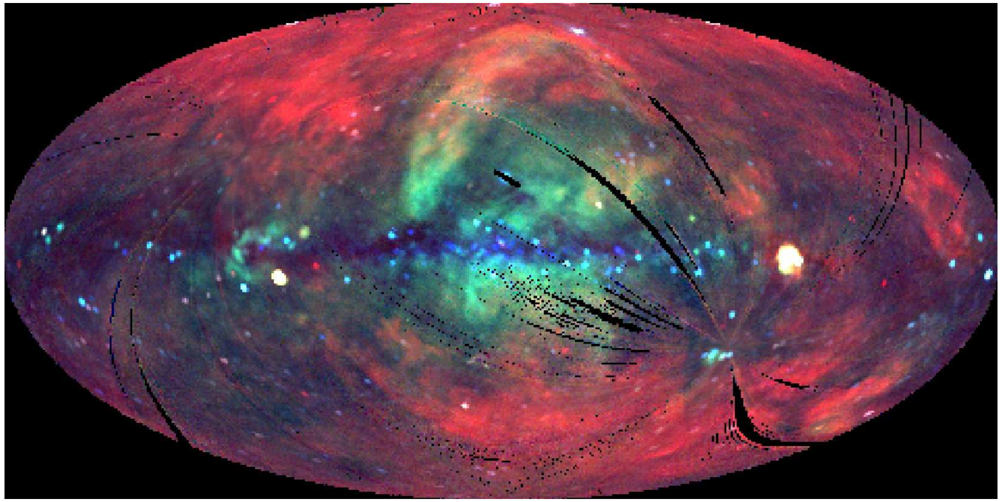
J. Dickey/F. Lockman/SkyView

Distribution of H I ($\lambda = 21\,cm$)



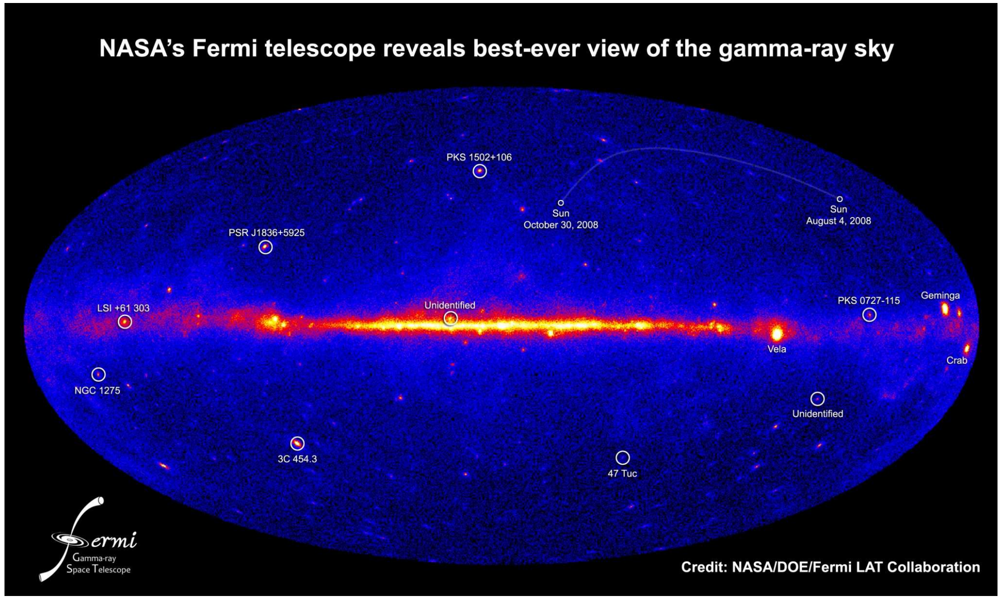
UCB/STScI

Extreme UV from *EUVE* (70–760Å)



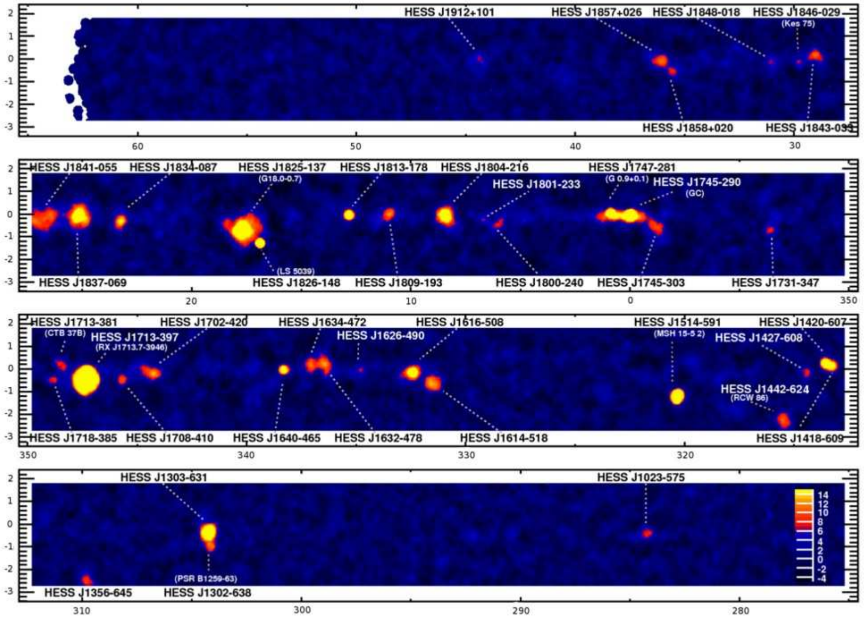
MPE/S. Snowden/M. Freyberg

X-rays from *ROSAT* All Sky Survey (0.1–2.0 keV)



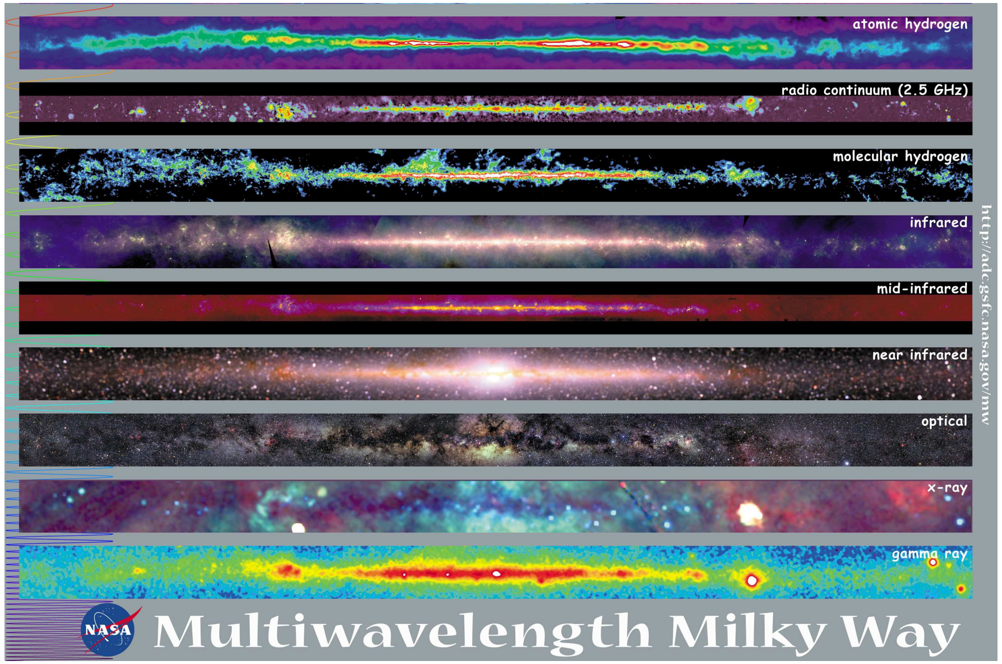
NASA/DOE/International LAT Team, see also Abdo et al. (2009)

γ-rays from *Fermi* ($>$100 MeV)

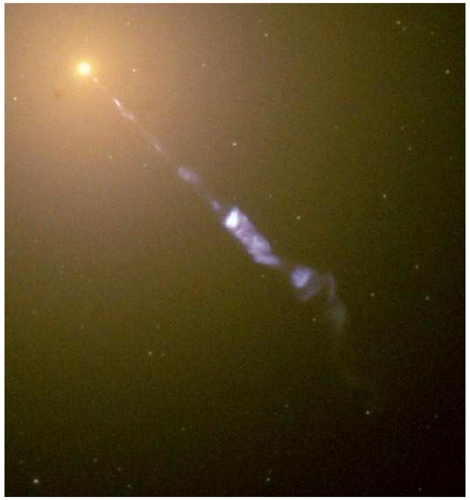


`http://www.mpi-hd.mpg.de/hfm/HESS/pages/home/som/2007/12/`

MW plane in TeV radiation from *H.E.S.S.*



1918: H. Curtis



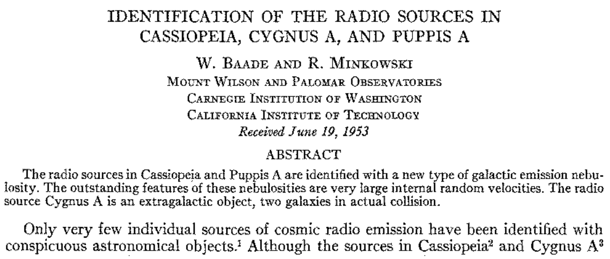
HST

1918: Heber D. Curtis: “[M87 exhibits] a curious straight ray. . . apparently connected with the nucleus by a thin line of matter”.

$\Longrightarrow$ M87 contains an optical jet

1954: W. Baade and R. Minkowski

W. Baade (Mt. Wilson Obs.)



IDENTIFICATION OF THE RADIO SOURCES IN CASSIOPEIA, CYGNUS A, AND PUPPIS A

W. BAADE AND R. MINKOWSKI
MOUNT WILSON AND PALOMAR OBSERVATORIES
CARNEGIE INSTITUTION OF WASHINGTON
CALIFORNIA INSTITUTE OF TECHNOLOGY
Received June 19, 1953

ABSTRACT

The radio sources in Cassiopeia and Puppis A are identified with a new type of galactic emission nebulosity. The outstanding features of these nebulosities are very large internal random velocities. The radio source Cygnus A is an extragalactic object, two galaxies in actual collision.

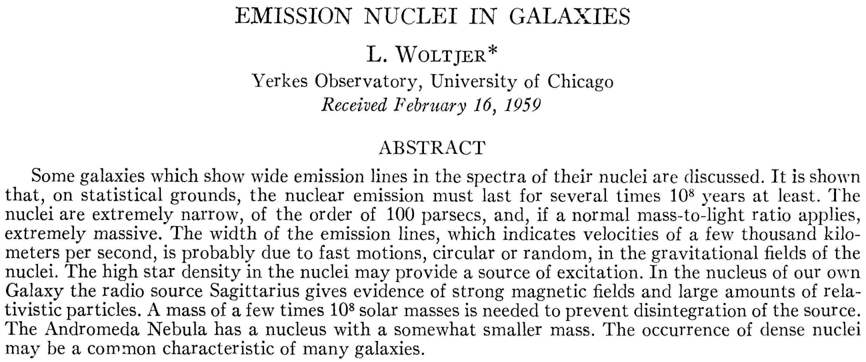
Only very few individual sources of cosmic radio emission have been identified with conspicuous astronomical objects.[1] Although the sources in Cassiopeia[2] and Cygnus A[3]

(Baade & Minkowski, 1954)

1954: Walter Baade and Rudolph Minkowski: Bright radio sources have galaxies as optical counterparts

Cyg A: 2nd brightest radio source on the sky.

1959: L. Woltjer



EMISSION NUCLEI IN GALAXIES

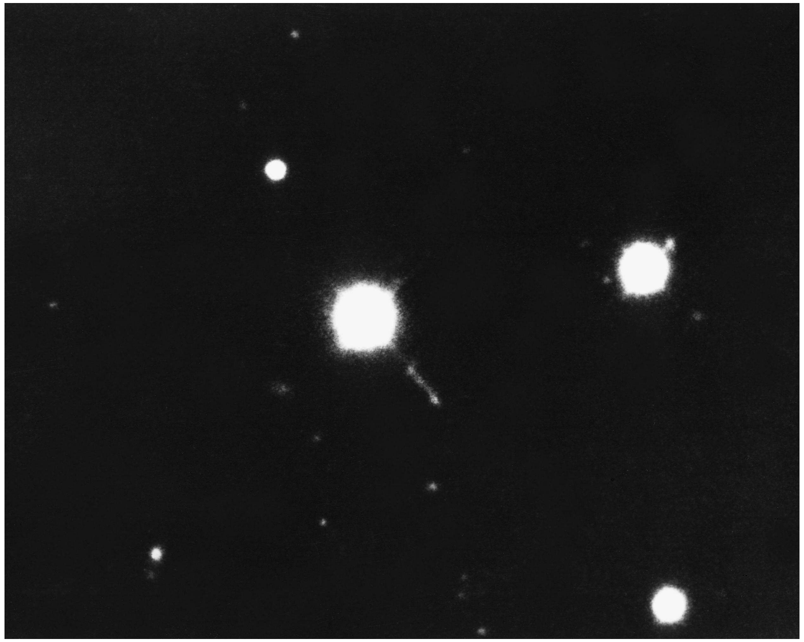
L. WOLTJER*
Yerkes Observatory, University of Chicago
Received February 16, 1959

ABSTRACT

Some galaxies which show wide emission lines in the spectra of their nuclei are discussed. It is shown that, on statistical grounds, the nuclear emission must last for several times 10^8 years at least. The nuclei are extremely narrow, of the order of 100 parsecs, and, if a normal mass-to-light ratio applies, extremely massive. The width of the emission lines, which indicates velocities of a few thousand kilometers per second, is probably due to fast motions, circular or random, in the gravitational fields of the nuclei. The high star density in the nuclei may provide a source of excitation. In the nucleus of our own Galaxy the radio source Sagittarius gives evidence of strong magnetic fields and large amounts of relativistic particles. A mass of a few times 10^8 solar masses is needed to prevent disintegration of the source. The Andromeda Nebula has a nucleus with a somewhat smaller mass. The occurrence of dense nuclei may be a common characteristic of many galaxies.

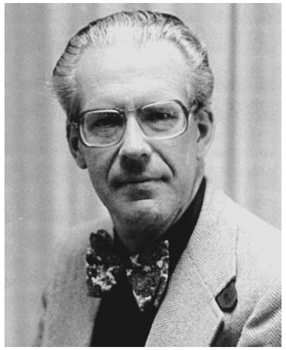
(Woltjer, 1959)

1959: Lodewijk Woltjer: Objects must have very large masses.

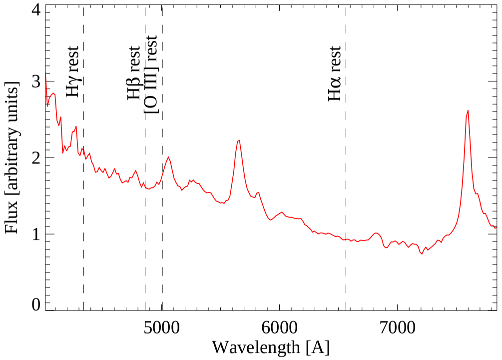


3C273 (4 m Myall telescope, NOAO/AURA/NSF)

1963: M. Schmidt



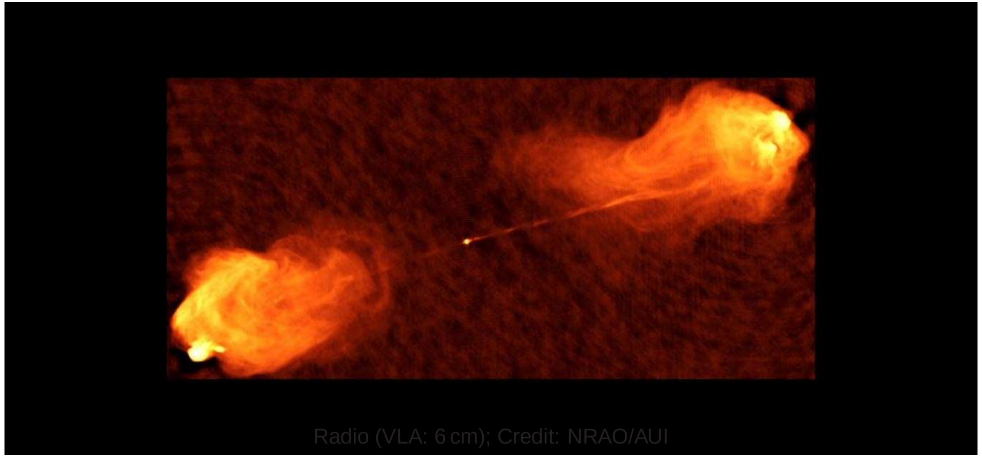
M. Schmidt (Caltech)



3C273 (Rondi et al., Pic du Midi)

1963: Maarten Schmidt: 3C273

The powerful radio galaxy Cygnus A at $z = 0.057$ ($d = 230$ Mpc).

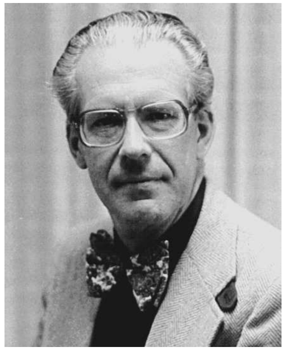


Radio (VLA: 6 cm); Credit: NRAO/AUI

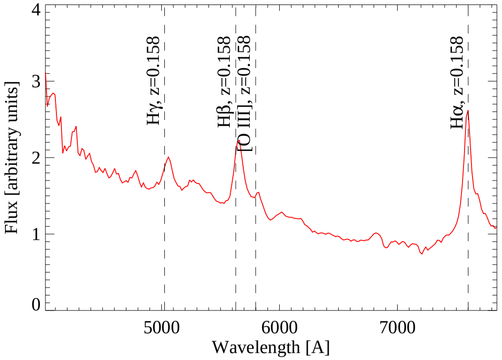
Size: $\sim$ 2.2 arcmin $\sim$ 600000 ly, about eight times the size of the milky way!

Radio morphology: Core – Jets – Hotspots – Lobes

1963: M. Schmidt



M. Schmidt (Caltech)



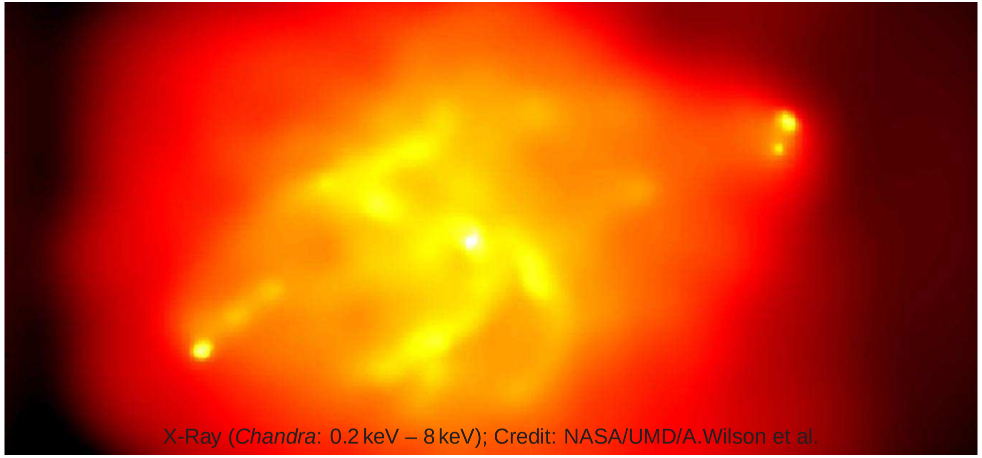
3C273 (Rondi et al., Pic du Midi)

1963: Maarten Schmidt: 3C273 has $z = 0.158 \Longrightarrow$ objects are far away!

$z = 0.158$ corresponds to $d = 1.74$ Gpc (3 billion ly)

shortly after this: 1963: J. Greenstein and Th. Matthews: 3C48 has $z = 0.368$

The powerful radio galaxy Cygnus A at $z = 0.057$ ($d = 230$ Mpc).

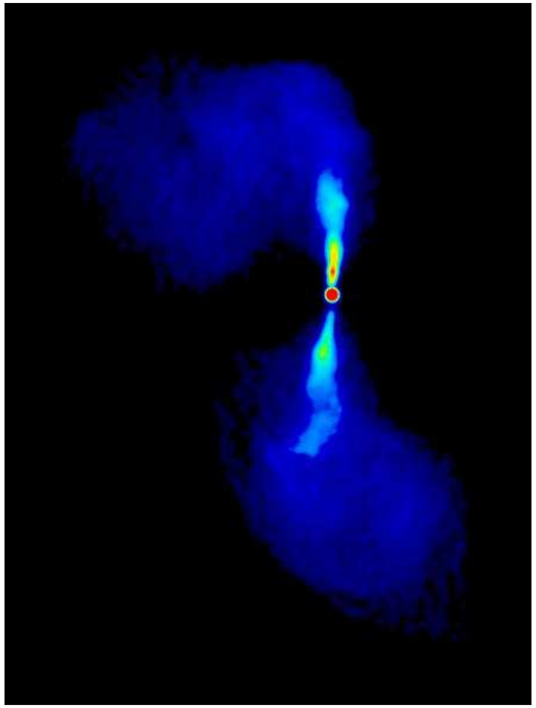


X-Ray (*Chandra*: 0.2 keV – 8 keV); Credit: NASA/UMD/A.Wilson et al.

Size: $\sim$ 2.2 arcmin $\sim$ 600000 ly, about eight times the size of the milky way!

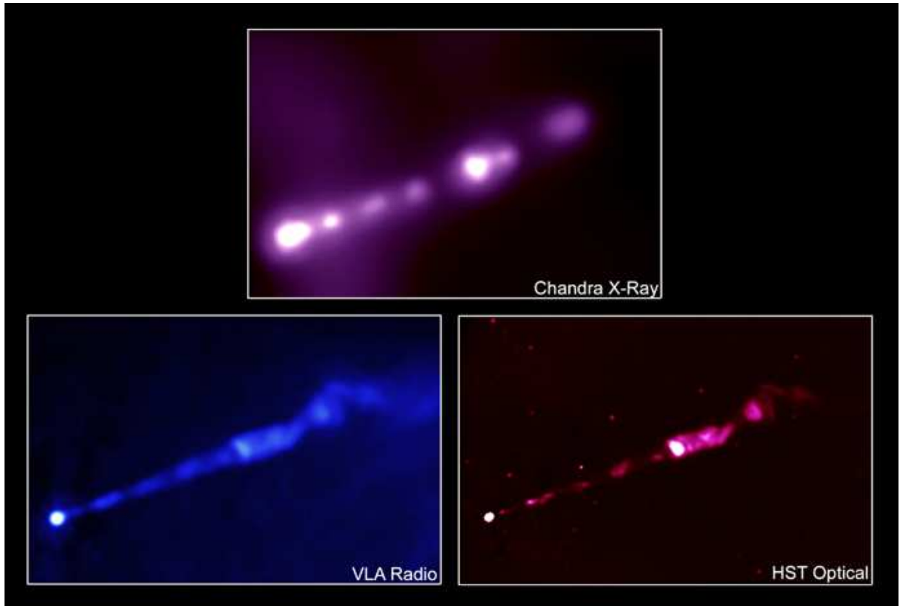
Radio morphology: Core – Jets – Hotspots – Lobes

X-Ray morphology: Nucleus – Cavity – Hotspots



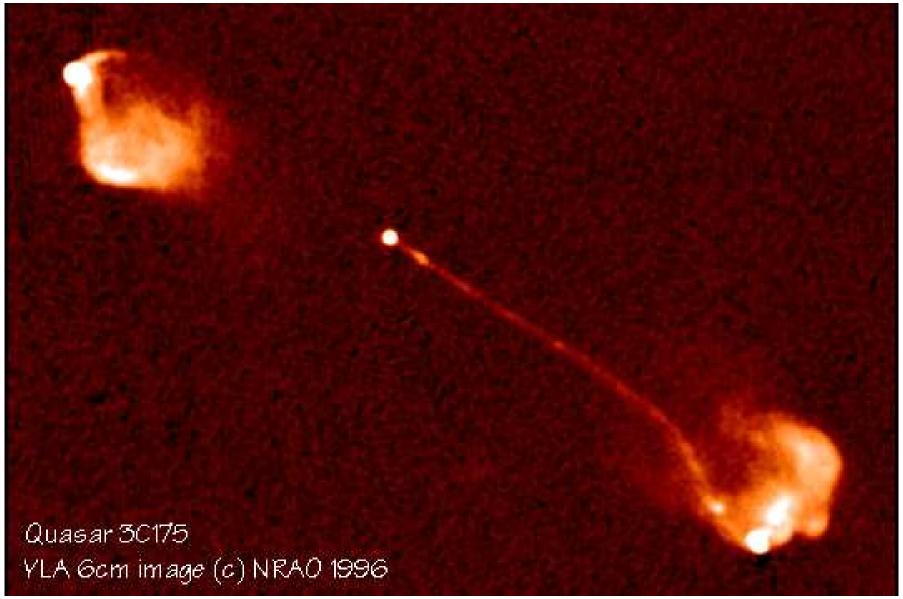
Radio image of M84 (3C272.1):
A typical Fanaroff Riley Type 1
Galaxy

Laing & Bridle (1987); VLA 4885 MHz,
$134'' \times 170''$



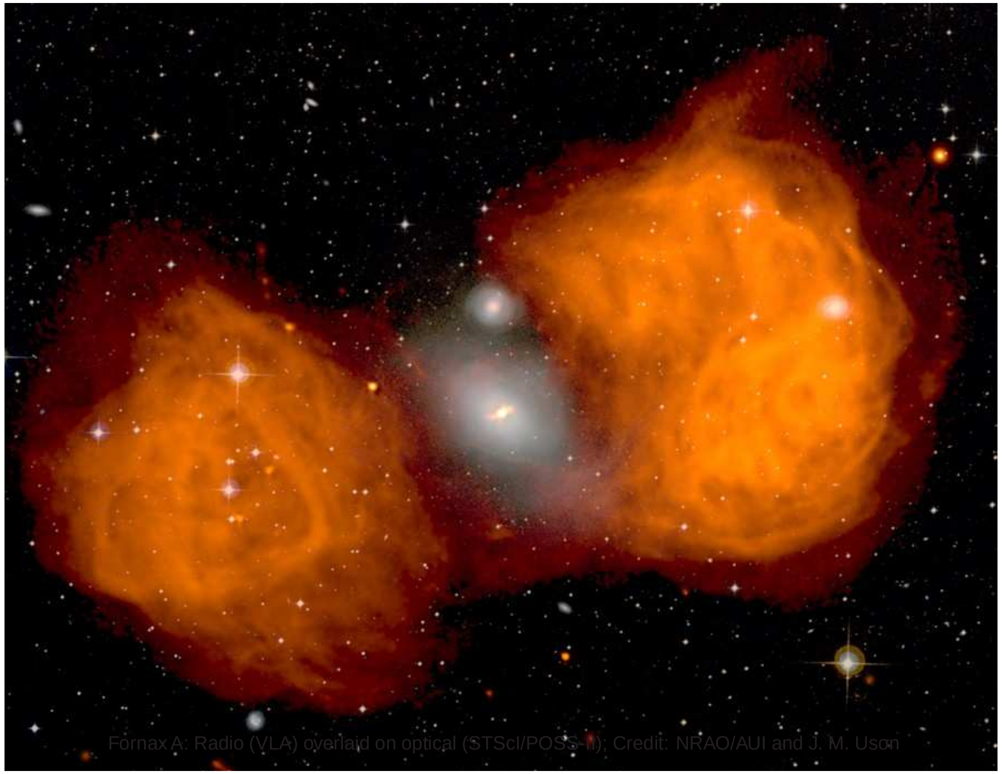
X-ray: NASA/CXC/MIT/H.Marshall et al. Radio: F.Zhou, F.Owen (NRAO), J.Biretta (STScI)
Optical: NASA/STScI/UMBC/E.Perlman et al.

Jets are visible in all wavebands



A. Bridle (priv. comm.)

Radio image of 3C175 ($z = 0.768$):
A typical FR 2 Galaxy



Fornax A: Radio (VLA) overlaid on optical (STScI/POSS-II); Credit: NRAO/AUI and J. M. Uson

1943: C. Seyfert

NUCLEAR EMISSION IN SPIRAL NEBULAE*

Carl K. Seyfert†

ABSTRACT

Spectrograms of dispersion 37–200 A/mm have been obtained of six extragalactic nebulae with high-excitation nuclear emission lines superposed on a normal G-type spectrum. All the stronger emission lines from λ 3727 to λ 6731 found in planetaries like NGC 7027 appear in the spectra of the two brightest spirals observed, NGC 1068 and NGC 4151.

Apparent relative intensities of the emission lines in the six spirals were reduced to true relative intensities. Color temperatures of the continua of each spiral were determined for this purpose.

The observed relative intensities of the emission lines exhibit large variations from nebula to nebula. Profiles of the emission lines show that all the lines are broadened, presumably by Doppler motion, by amounts varying up to 8500 km/sec for the total width of the hydrogen lines in NGC 3516 and NGC 7469. The hydrogen lines in NGC 4151 have relatively narrow cores with wide wings, 7500 km/sec in total breadth. Similar wings are found for the Balmer lines in NGC 7469. The lines of the other ions show no evidence of wide wings. Some of the lines exhibit strong asymmetries, usually in the sense that the violet side of the line is stronger than the red.

In NGC 7469 the absorption K line of *Ca* II is shallow and 50 A wide, at least twice as wide as in normal spirals.

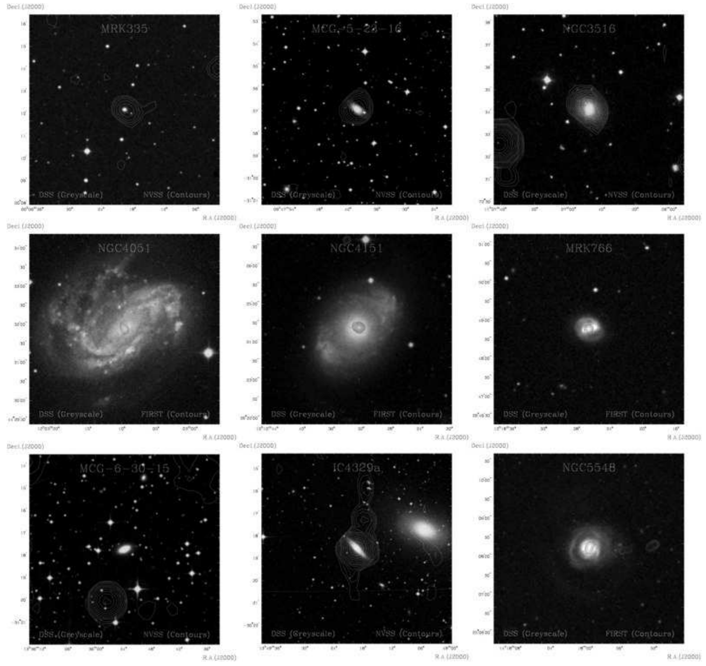
Absorption minima are found in six of the stronger emission lines in NGC 1068, in one line in NGC 4151, and one in NGC 7469. Evidence from measures of wave length and equivalent widths suggests that these absorption minima arise from the G-type spectra on which the emissions are superposed.

The maximum width of the Balmer emission lines seems to increase with the absolute magnitude of the nucleus and with the ratio of the light in the nucleus to the total light of the nebula. The emission lines in the brightest diffuse nebulae in other extragalactic objects do not appear to have wide emission lines similar to those found in the nuclei of emission spirals.

(Seyfert, 1943)

1943: Carl Seyfert: There is a class of spiral galaxies with optical *emission lines*

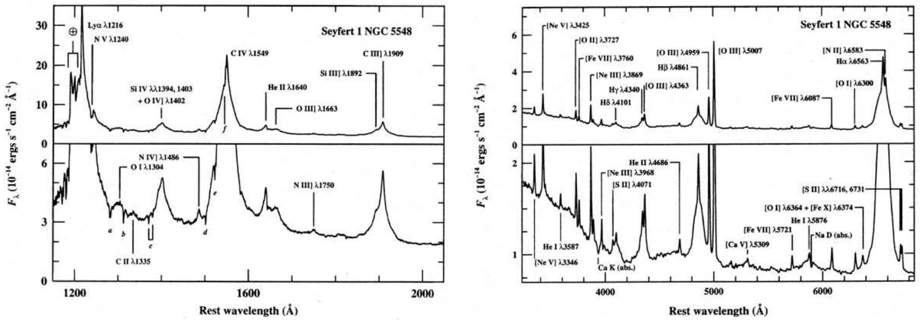
$\Longrightarrow$ Seyfert Galaxies



grey: optical; contours: radio (M. Kadler)

Seyfert Galaxies: point-like sources in the centers of galaxies, normally galaxy is detectable;
two types: Seyfert 1 galaxies and Seyfert 2 galaxies.

1943: C. Seyfert

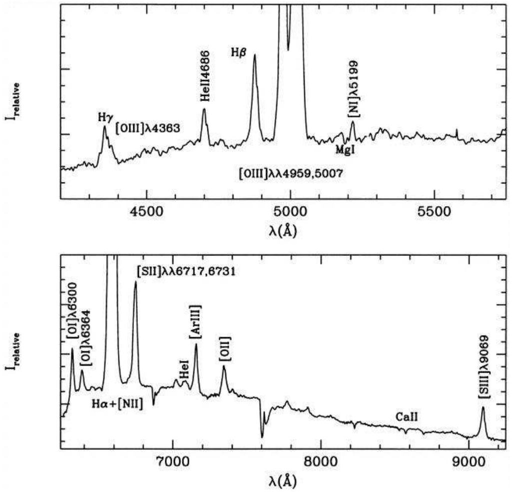


Seyfert 1 galaxies

- broad allowed lines (e.g., from H), with widths corresponding up to $10^4\,\mathrm{km\,s^{-1}}$ from a medium of high density ($n_\mathrm{e} \gtrsim 10^9\,\mathrm{cm^{-3}}$).
- Thin forbidden lines (e.g., $[\mathrm{O\,III}5007]$), FWHM $\sim$ few $\cdot\, 10^2\,\mathrm{km\,s^{-1}}$ from a thin medium ($n_\mathrm{e} \sim 10^3\,\mathrm{cm^{-3}} \dots 10^6\,\mathrm{cm^{-3}}$).

Velocity width from Doppler effect: $\Delta\lambda/\lambda = v/c$.

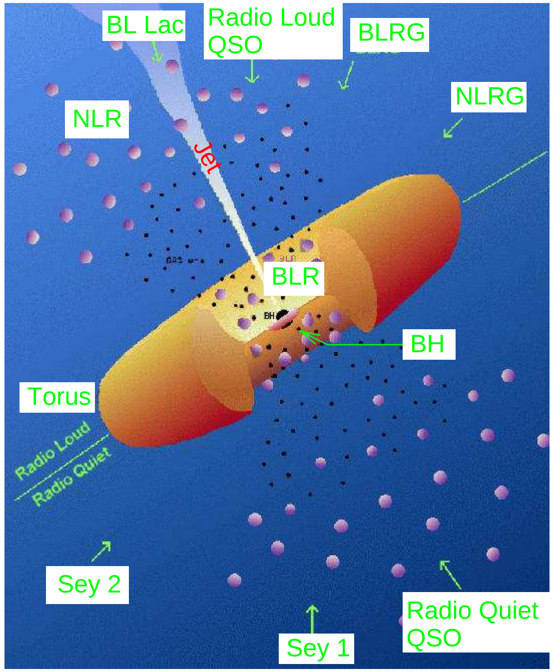
Seyfert 2



Spectrum of the Seyfert 2 galaxy NGC 1068:

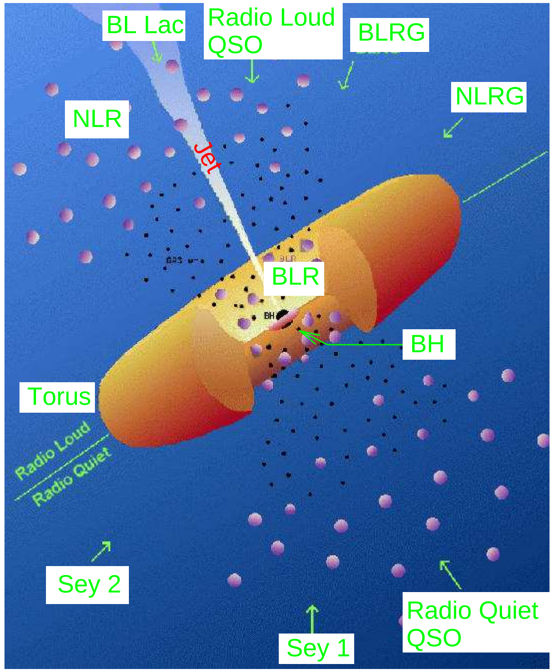
- weak continuum (compared to Seyfert 1s).
- thin forbidden lines, $\sim$ few $\cdot$ $10^2\,\mathrm{km\,s^{-1}}$.
- no broad lines

(García-Lorenzo, Mediavilla & Arribas, 1999, Fig. 4)



Unification: Assumes physics of all AGN is the same, phenomenology is due to different lines of sight.

(Urry & Padovani, 1995, Important: length scale is not linear!)



Physical properties:

Accretion disc: $r \sim 10^{-3}$ pc,
$n \sim 10^{15}\,\mathrm{cm}^{-3}$,
$kT \sim 50\,\mathrm{eV} \cdot r^{-3/4}$,
$v \sim 0.3c$ at the inner edge.

Broad Line Region (BLR): $r \sim$ 0.01–0.1 pc (=light days or less),
$n \sim 10^{10}\,\mathrm{cm}^{-3}$,
$v \sim 1000$–$5000\,\mathrm{km\,s}^{-1}$,
$T \sim 10^4$ K

Torus: $r \sim$ 1– few 10 pc,
$n \sim 10^3$–$10^6\,\mathrm{cm}^{-3}$,
T: cold

Narrow Line Region (NLR): $r \sim$ 100–1000 pc,
$n \sim 10^3$–$10^6\,\mathrm{cm}^{-3}$,
$v \sim$ few100 $\mathrm{km\,s}^{-1}$,
$T \sim 10^4$ K

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