

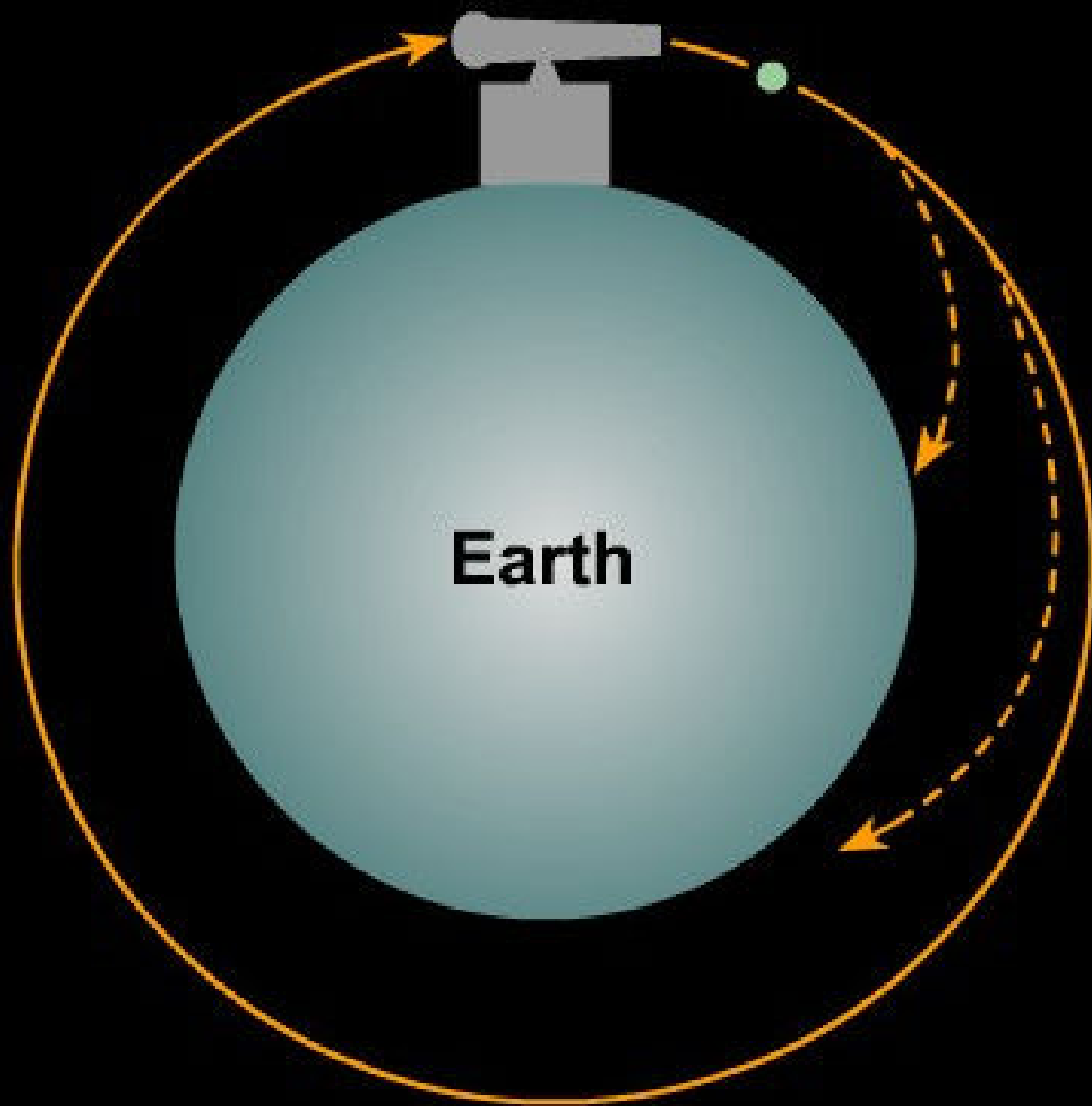
# Tajemnice czarnych dziur



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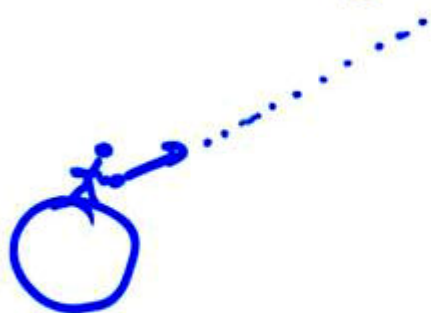
*Uniwersytet Warszawski*



**Newton's Orbital Cannon**



# Prędkość ucieczki



$$v = \sqrt{\frac{2GM}{r}}$$

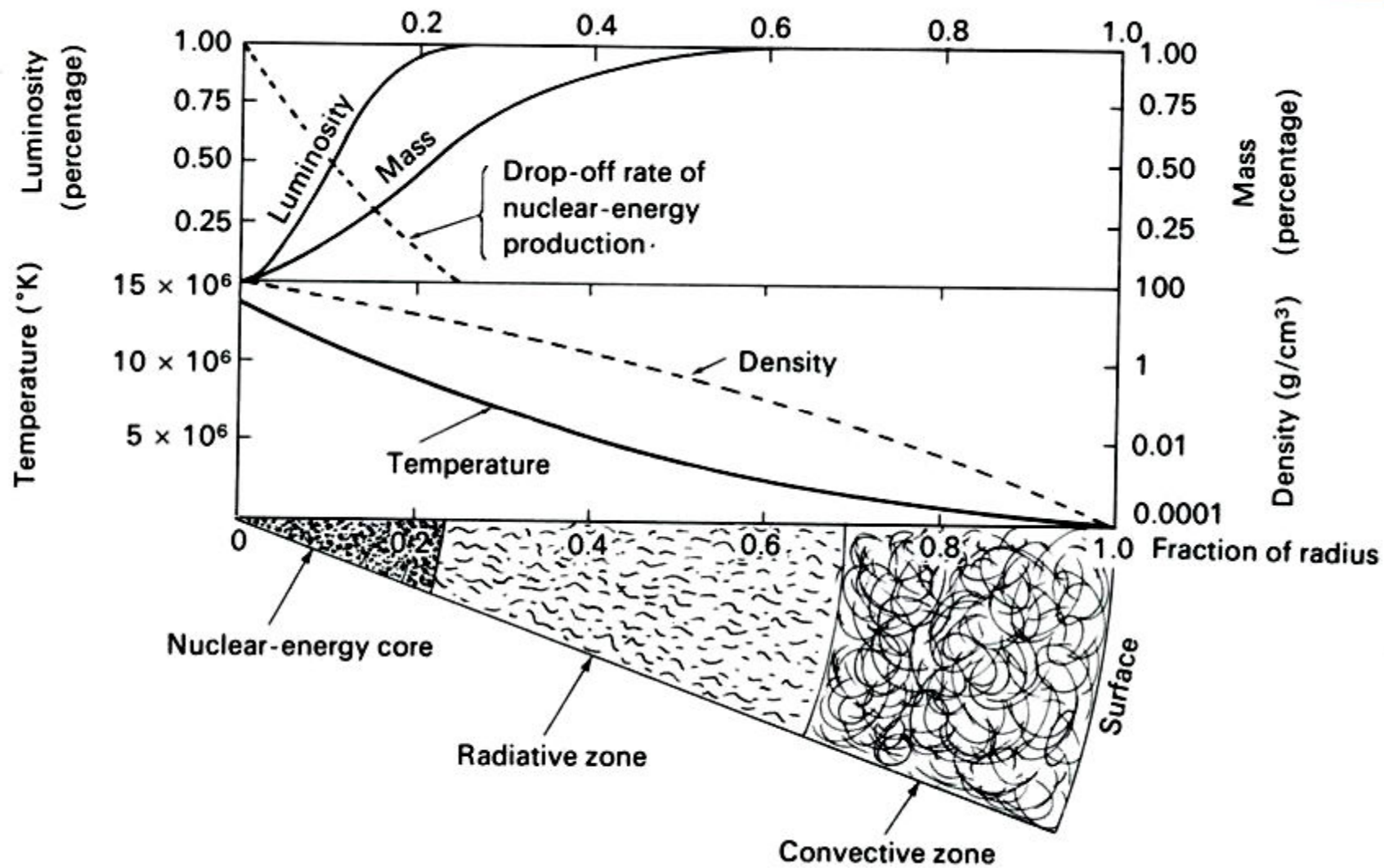
$$v \rightarrow c \quad r \rightarrow r_g = \frac{2GM}{c^2}$$

promień  
Schwarzschilda

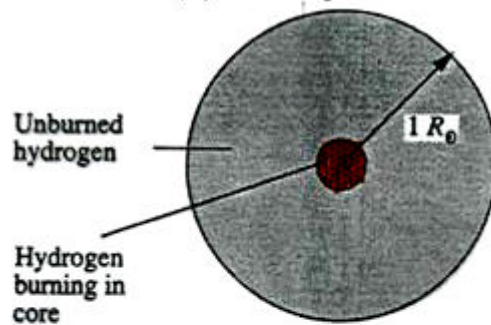
$$r_{g\odot} = 0.89 \text{ cm}$$

$$r_{g\oplus} = 3 \text{ km}$$

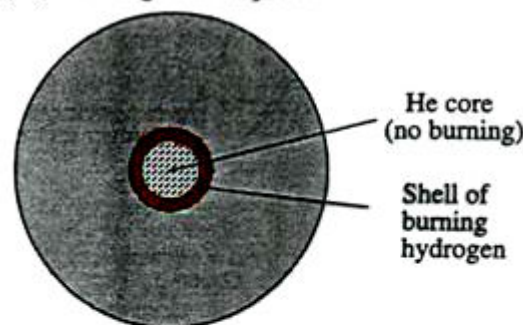
<http://sohowww.nascom.nasa.gov/>



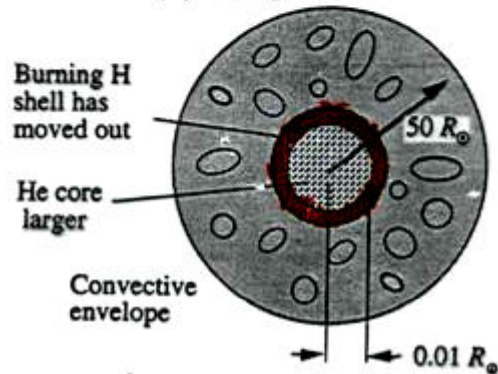
(a) Main sequence



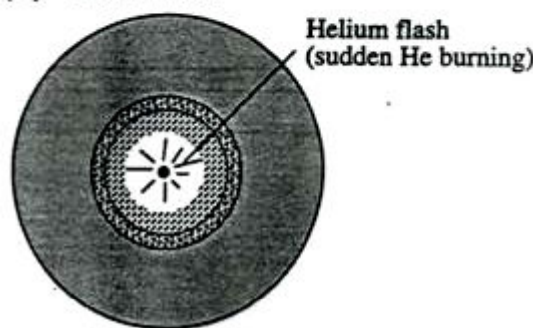
(b) Leaving main sequence



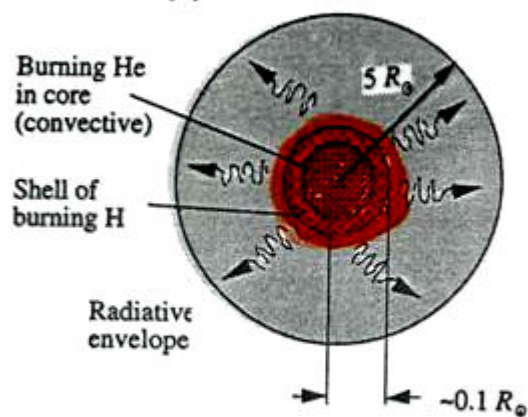
(c) Red giant



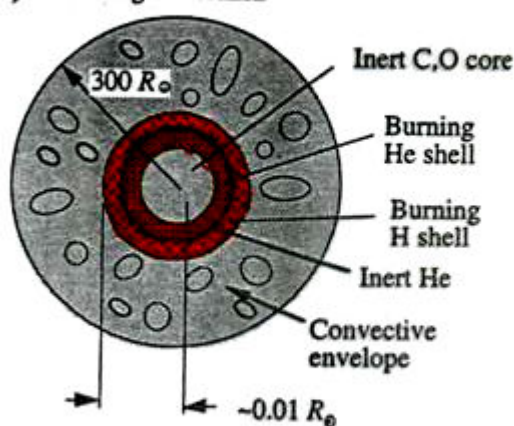
(d) Helium flash



(e) Horizontal branch



(f) Second giant branch



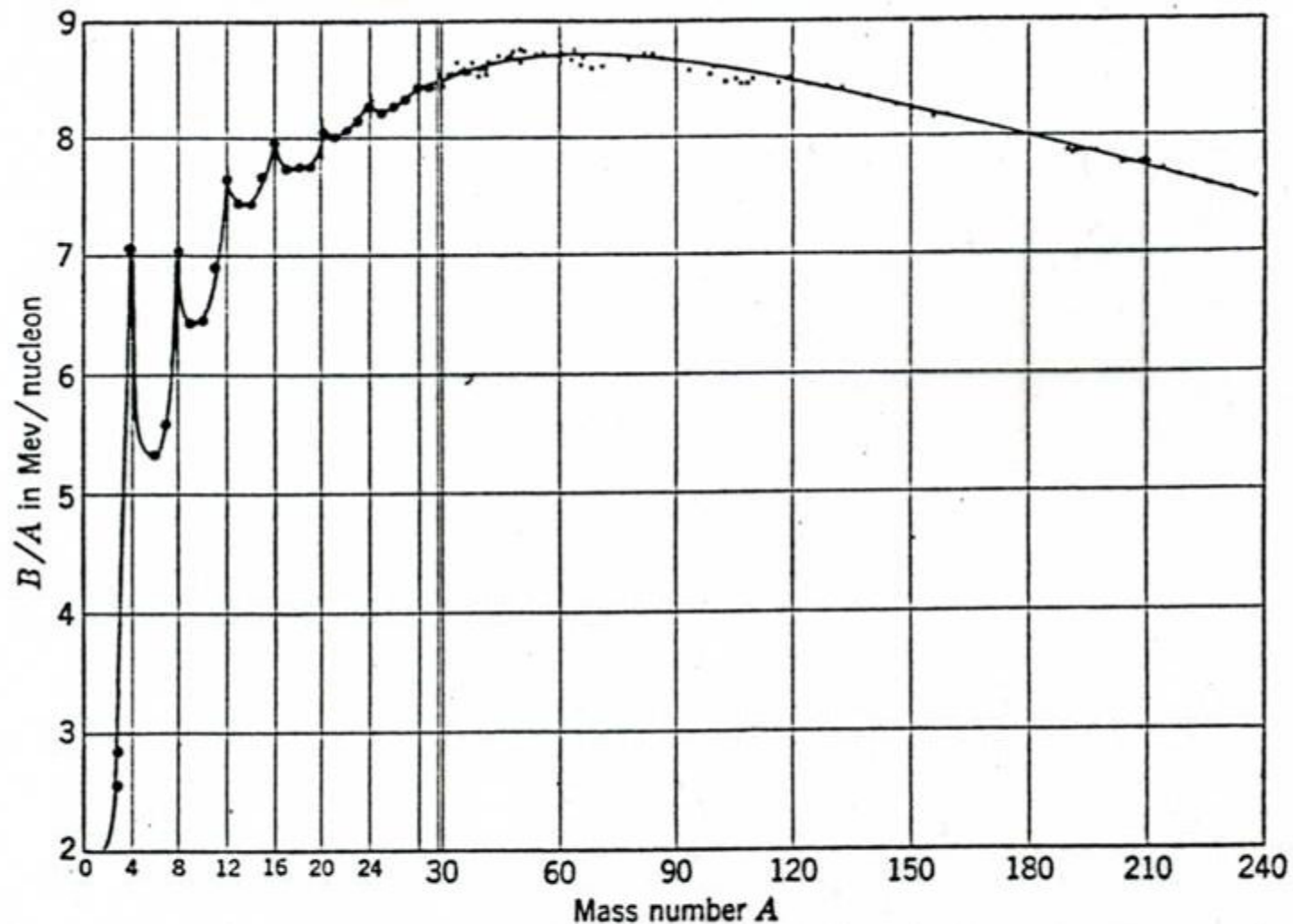
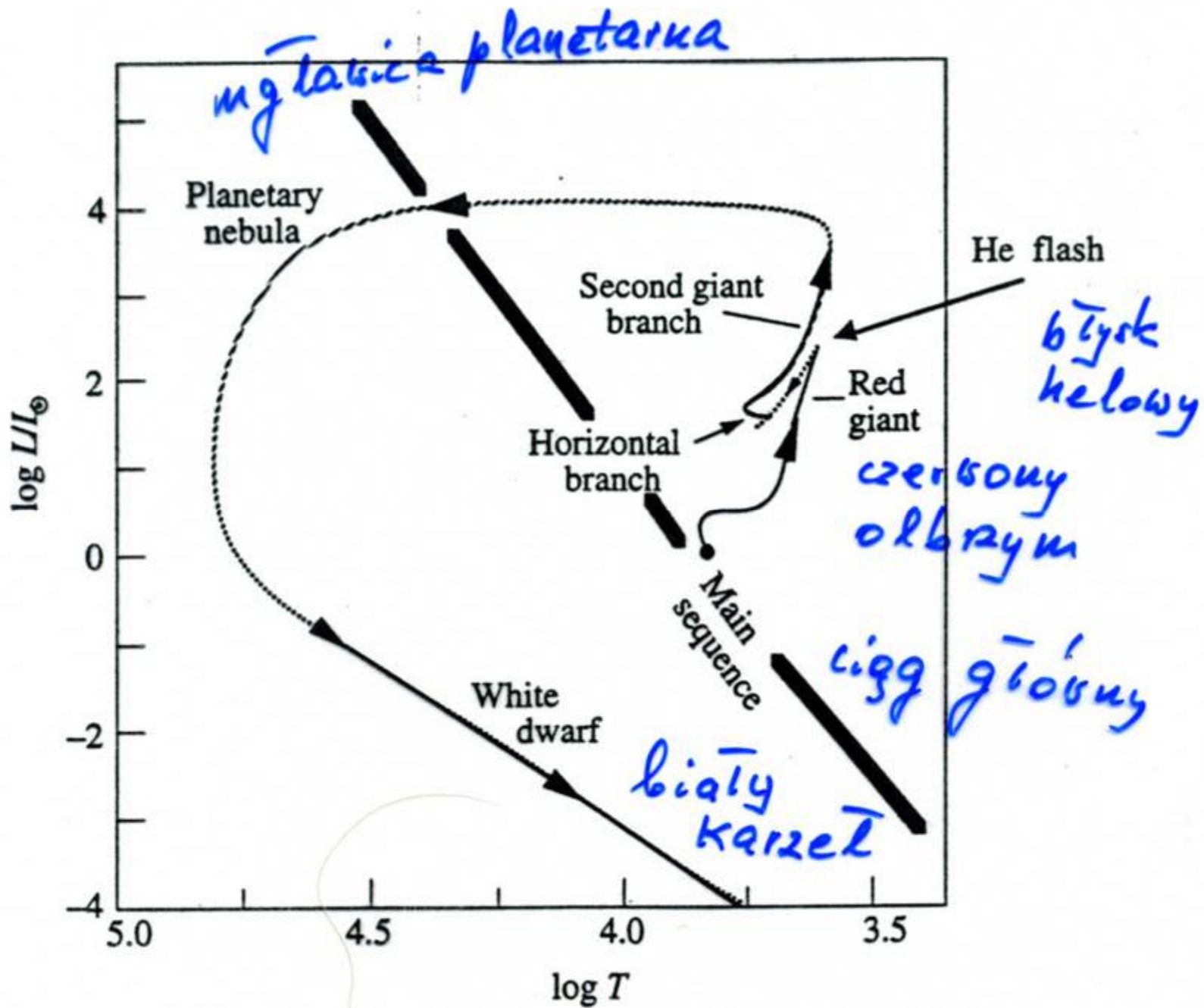
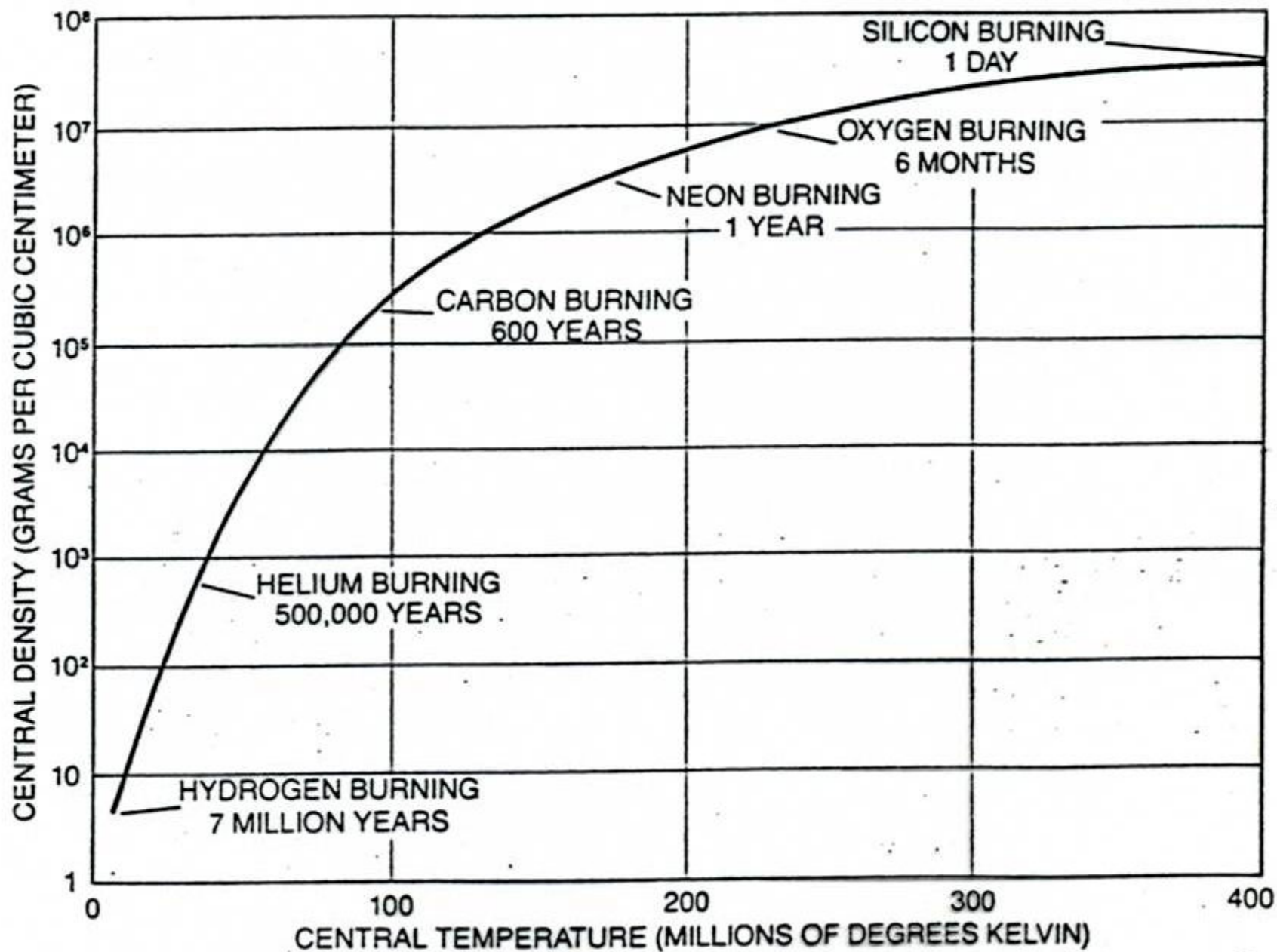


Fig. 3.1 Average binding energy  $B/A$  in Mev per nucleon for the naturally occurring nuclides (and  $\text{Be}^8$ ), as a function of mass number  $A$ . Note the change of magnification in the  $A$  scale at  $A = 30$ . The Pauli four-shells in the lightest nuclei are evident. For  $A \geq 16$ ,  $B/A$  is roughly constant; hence, to a first approximation,  $B$  is proportional to  $A$ .



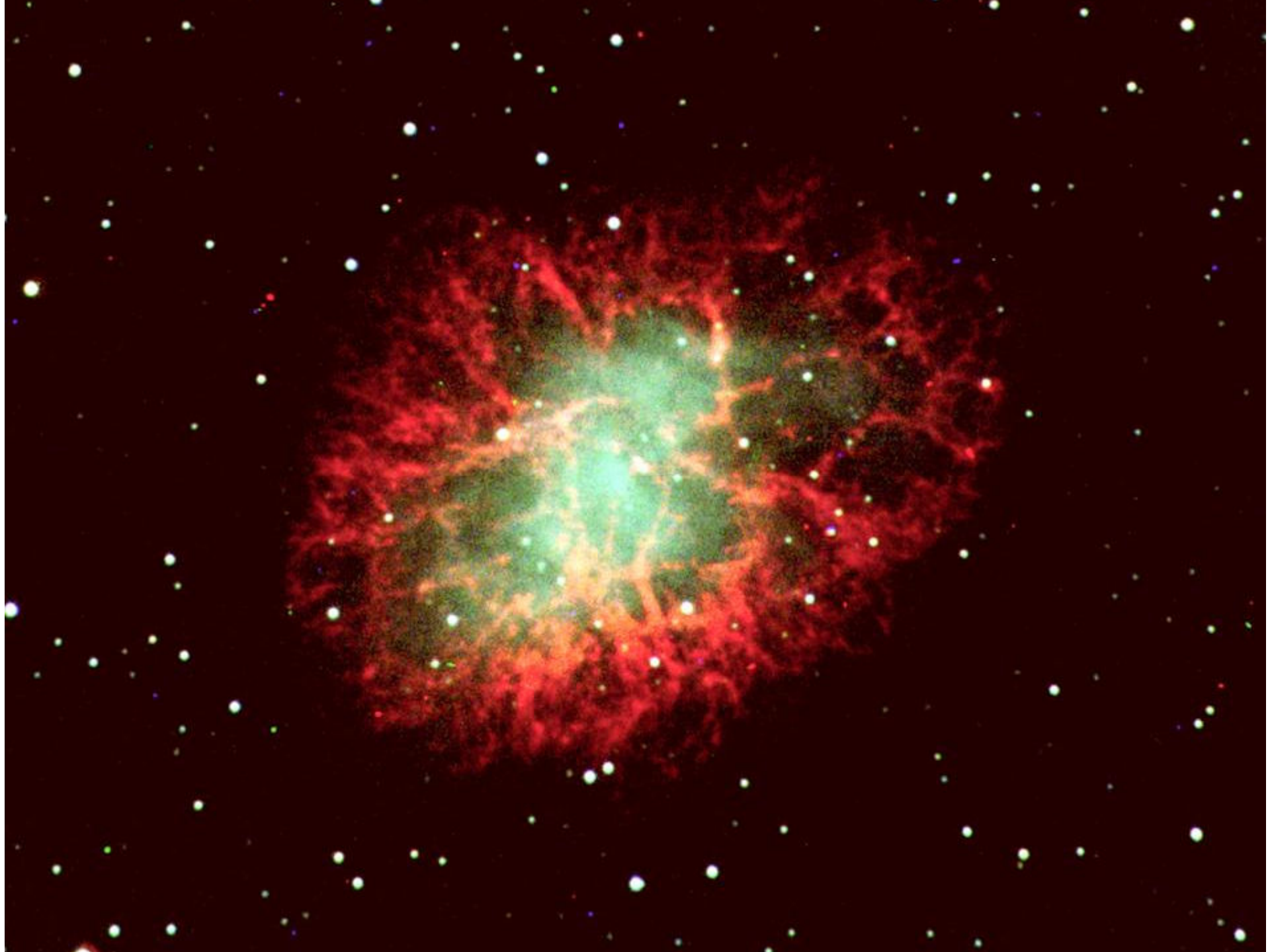


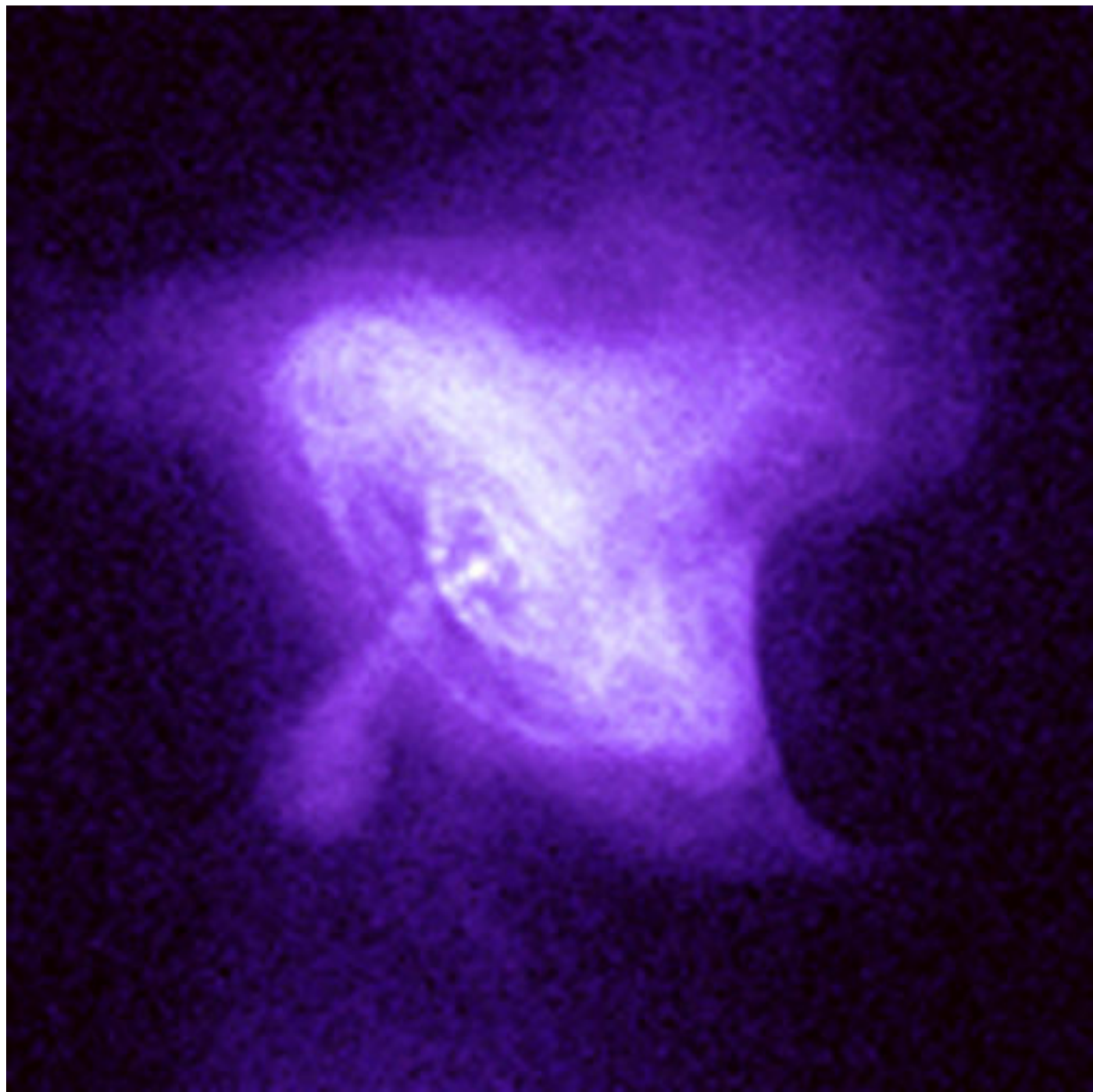
# Ostatnie fazy ewolucji gwiazd (i co po nich zostaje)

$0.085 \leq \frac{M_{in}}{M_{\odot}} \leq (8-12) \longrightarrow$  biały karzeł  
 $M < 1.4 M_{\odot}$  granica  
Chandrasekhara  
  
-----> mgławica  
planetarna

$(8-12) \leq \frac{M_{in}}{M_{\odot}} < \sim 20 \longrightarrow$  gwiazda  
wybuch  
supernowej neutronowa  
 $M \lesssim 3 M_{\odot}$

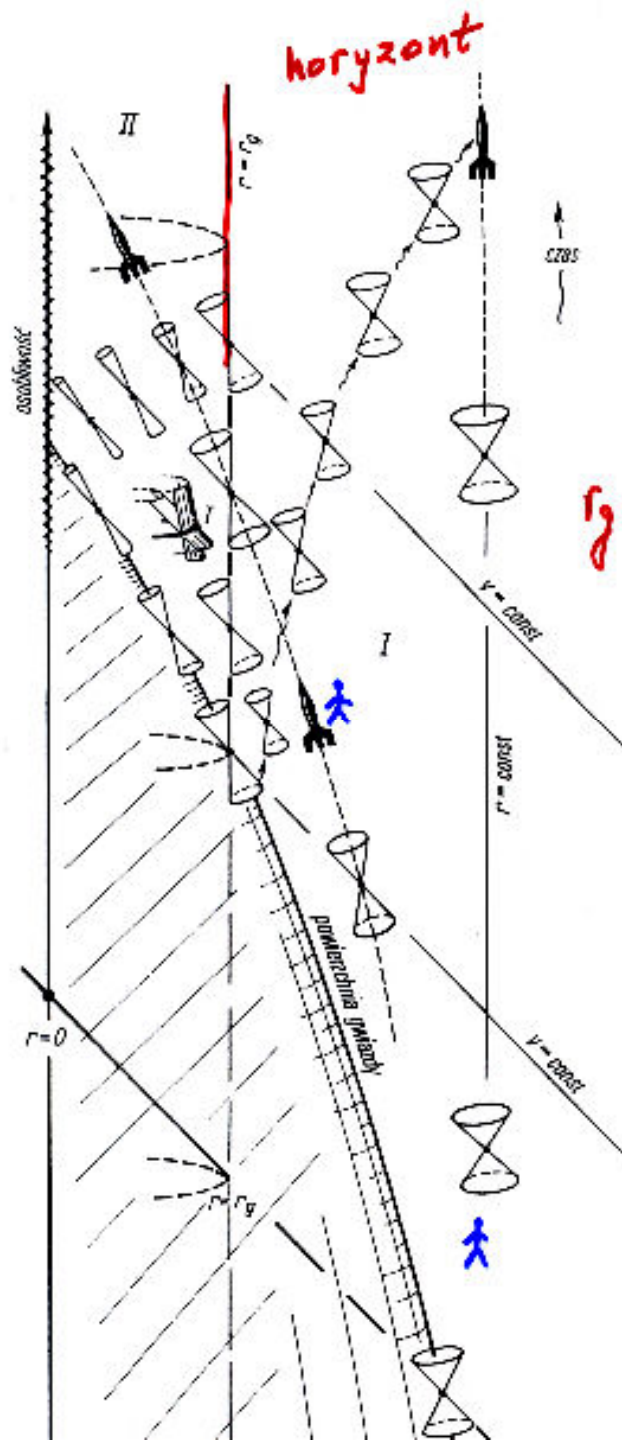
$\frac{M_{in}}{M_{\odot}} > \sim 20 \longrightarrow$  czarna  
dziura  
wybuch  
supernowej  
 $M > 3 M_{\odot}$



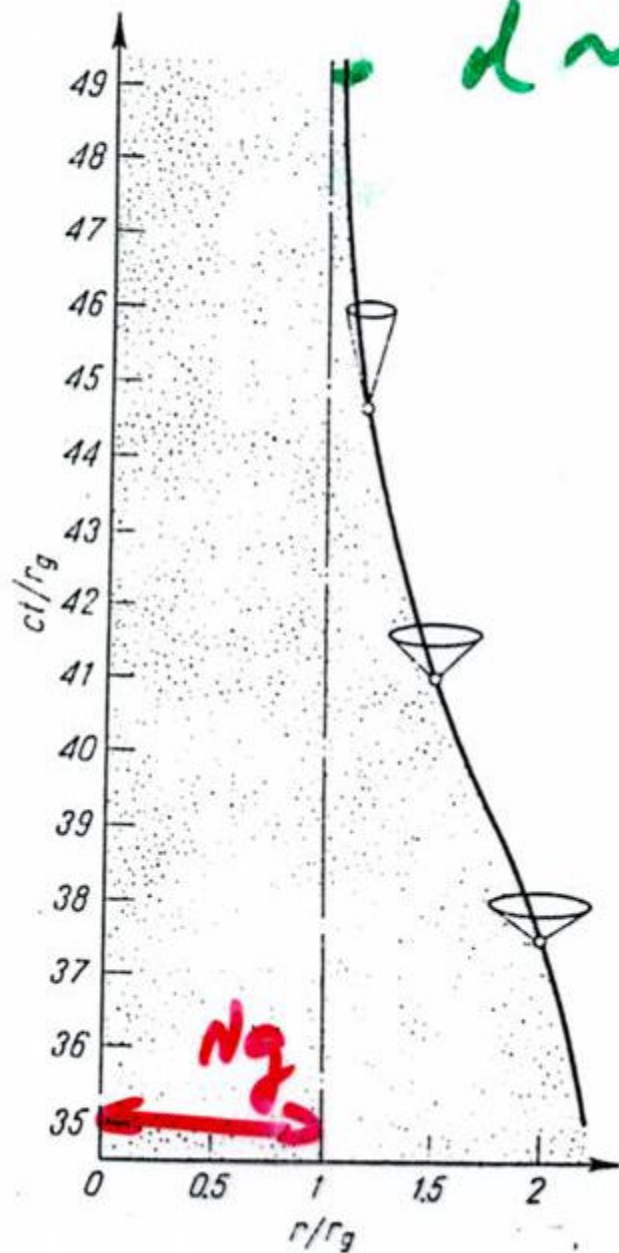


$$\rho \rightarrow \infty$$

$$R \rightarrow 0$$



$$r_g = \frac{2GM}{c^2}$$

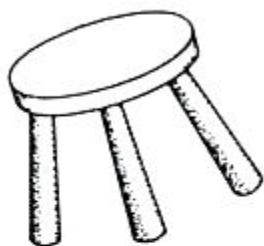


$$d \sim r_g + d_0 e^{-r/r_g t}$$

$$L = L_0 e^{-r/r_g t}$$

$$r_g = \frac{2GM}{c^2}$$

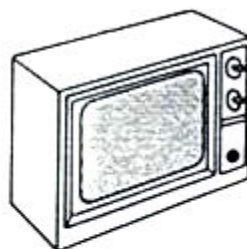




Angular Momentum



Strangeness



Baryons

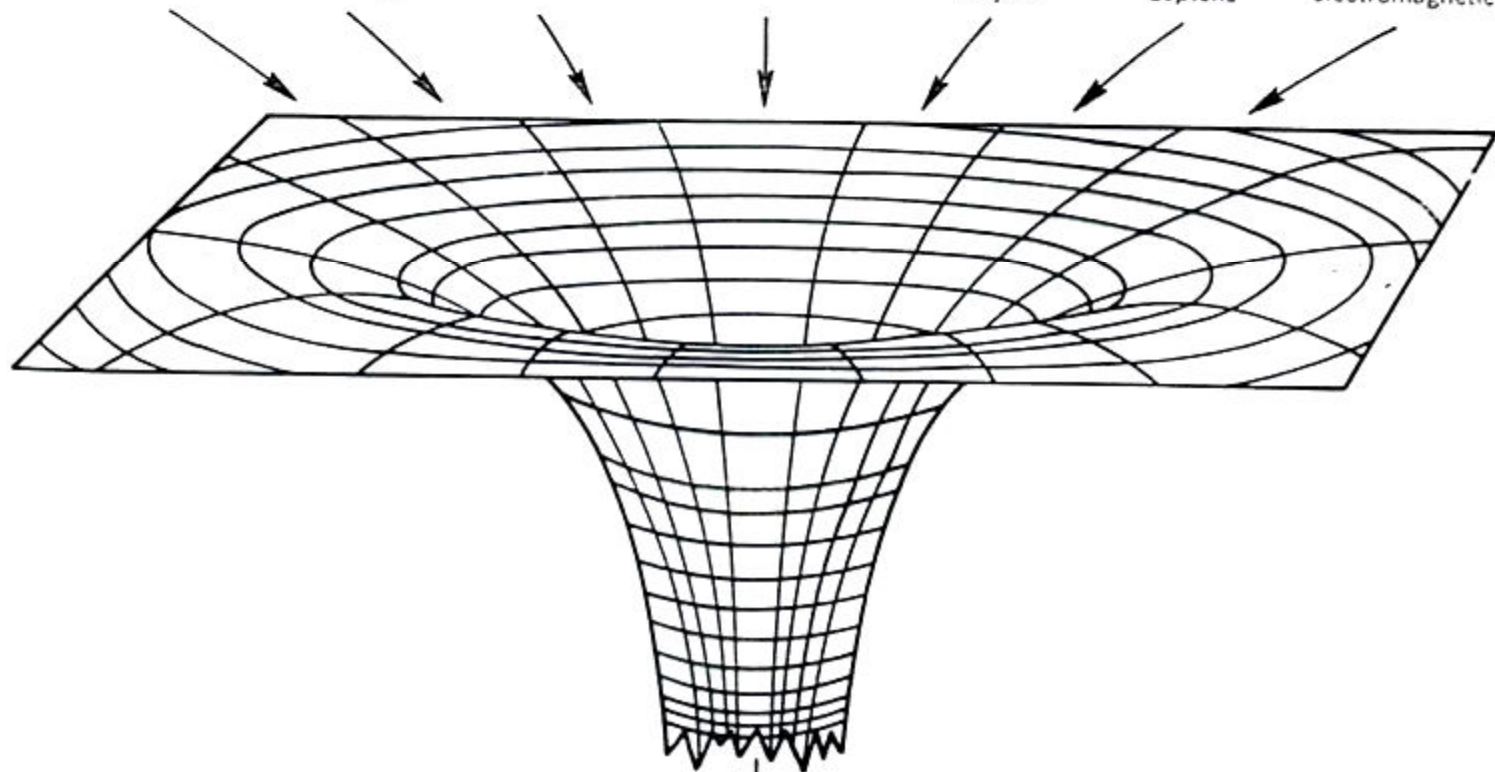


Gravitational and  
electromagnetic waves

Mass

Charge

Leptons



Mass  
Charge  
Angular Momentum

# BLACK HOLES

non rotating  
(Schwarzschild)

$$M \neq 0, J = 0$$

$$r_g = \frac{2GM}{c^2}$$

M - mass

J - angular  
momentum

rotating  
(Kerr)

$$M \neq 0, J \neq 0$$

$$r_g = \frac{GM}{c^2} + \sqrt{\left(\frac{GM}{c^2}\right)^2 - \left(\frac{J}{Mc}\right)^2}$$

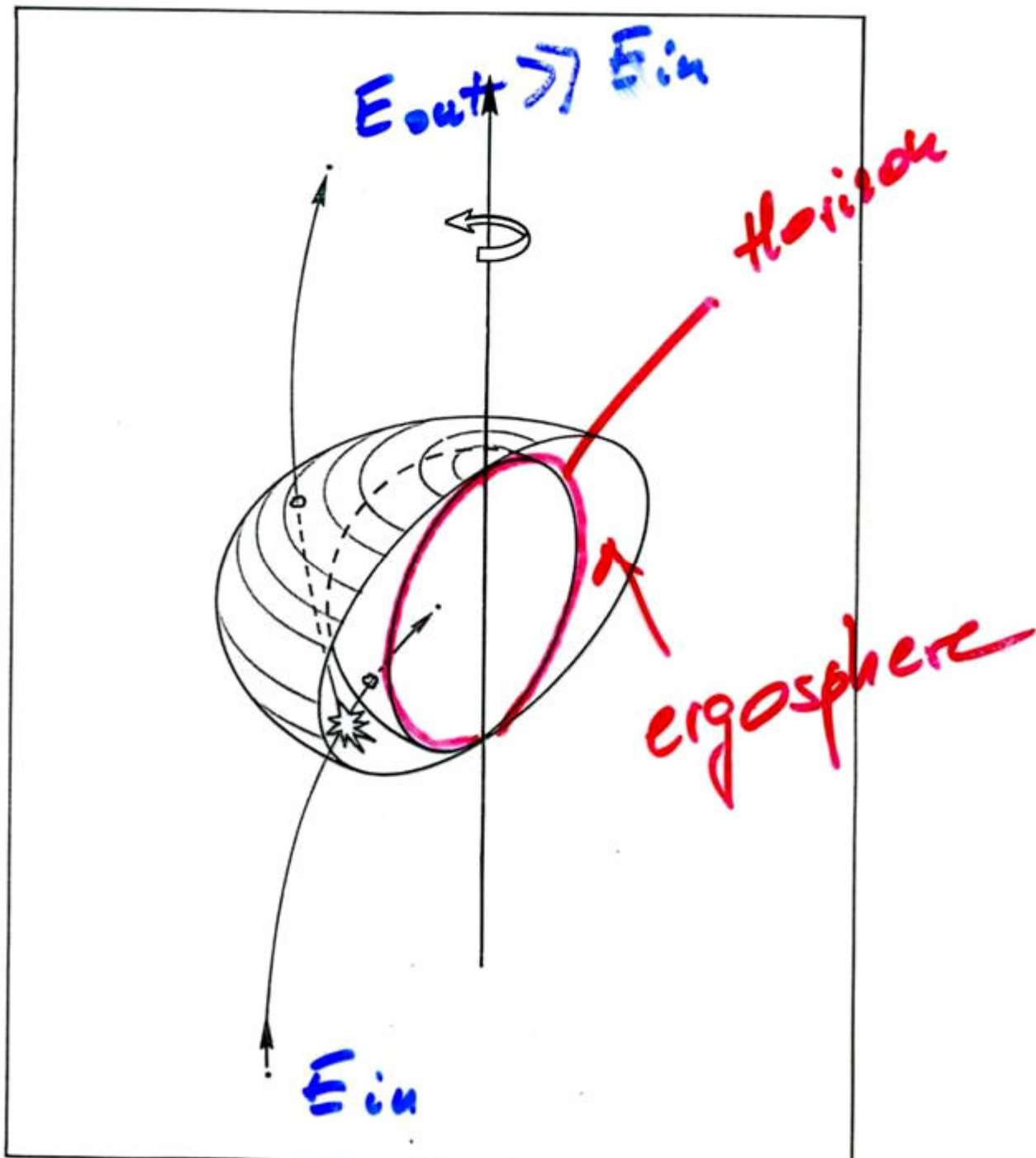
black holes can not  
rotate arbitrarily fast!

$$J_{\text{crit}} = \frac{GM^2}{c}$$

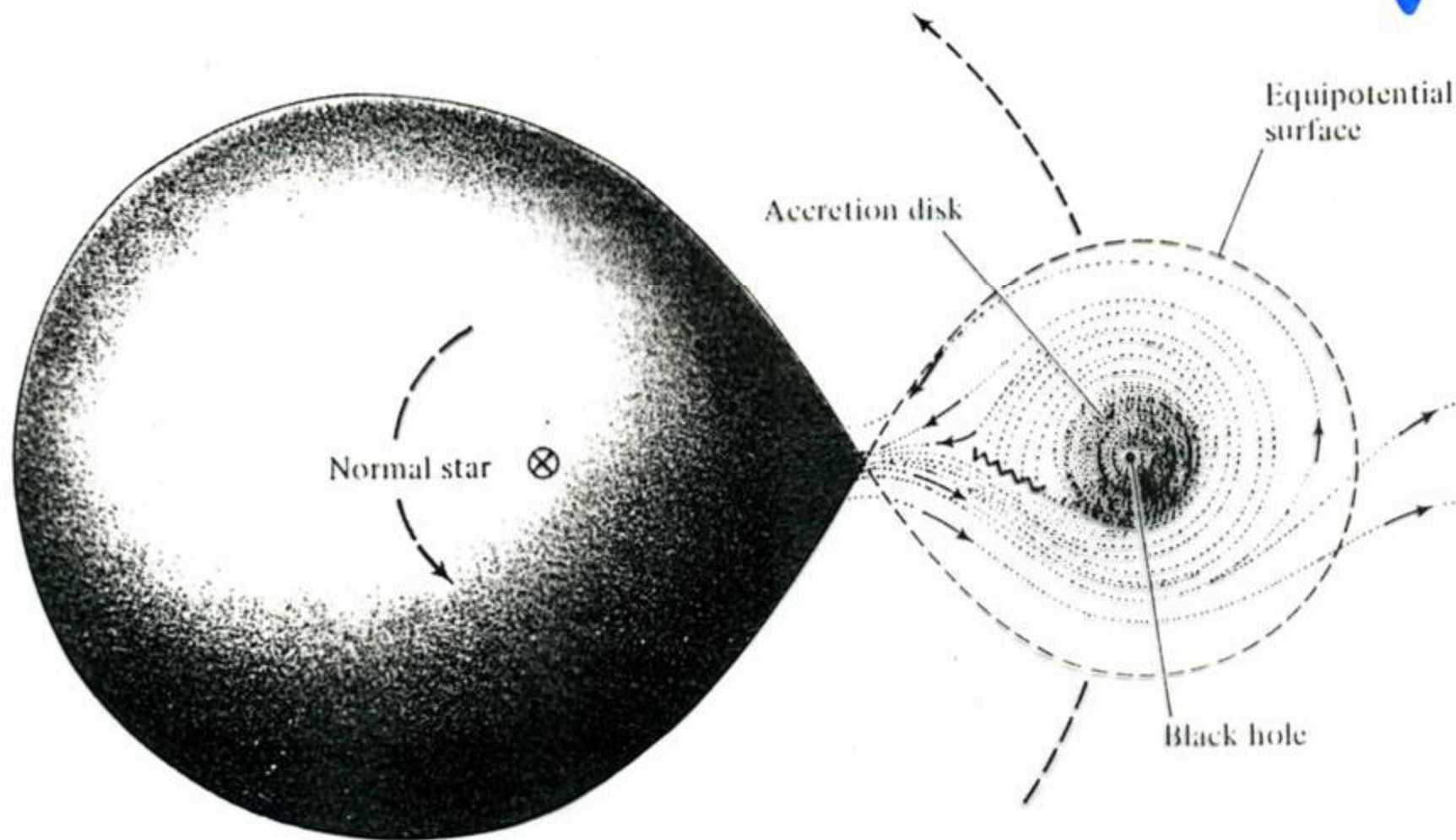
stellar black holes  $M \sim (3-40)M_\odot$

super massive black holes  $M \sim (10^6 \div 10^9)M_\odot$

$$M_{\text{BH}} \sim 3 \times 10^6 M_\odot$$

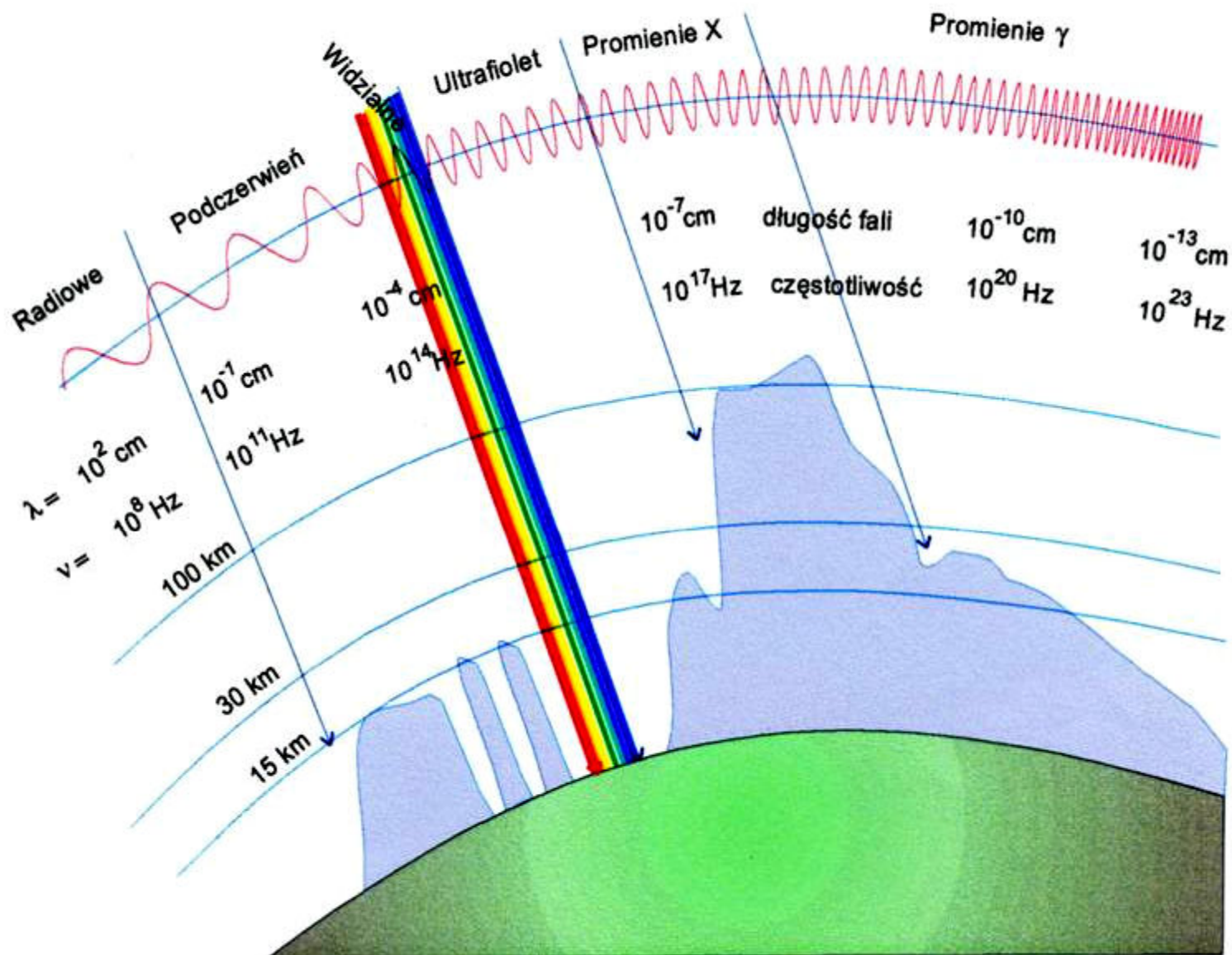


$T \sim 10^6 \text{ K}$   
X-rays

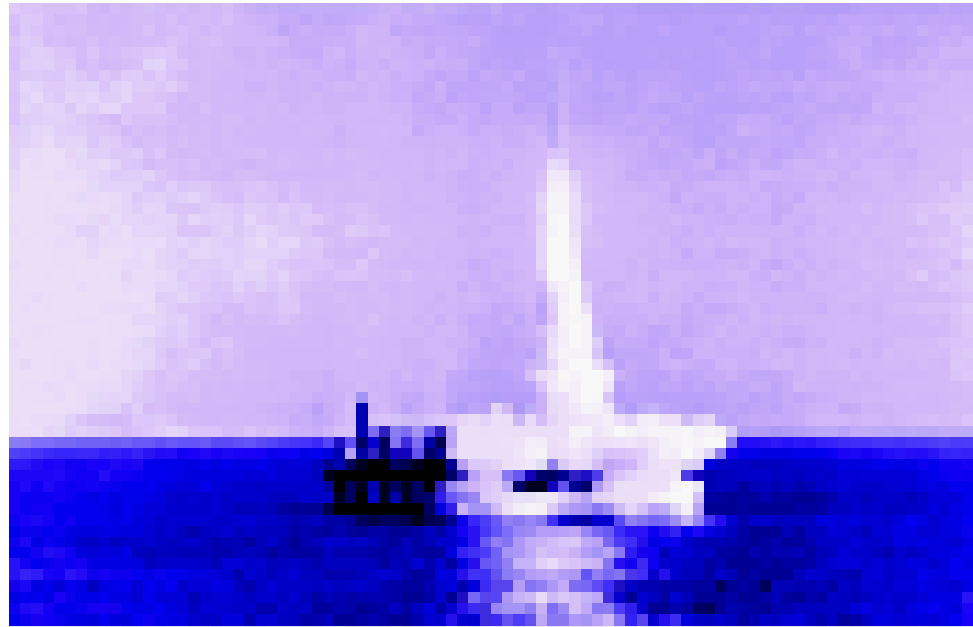


# Kiedy astronomiczne źródło X może zawierać czarną dziurę ?

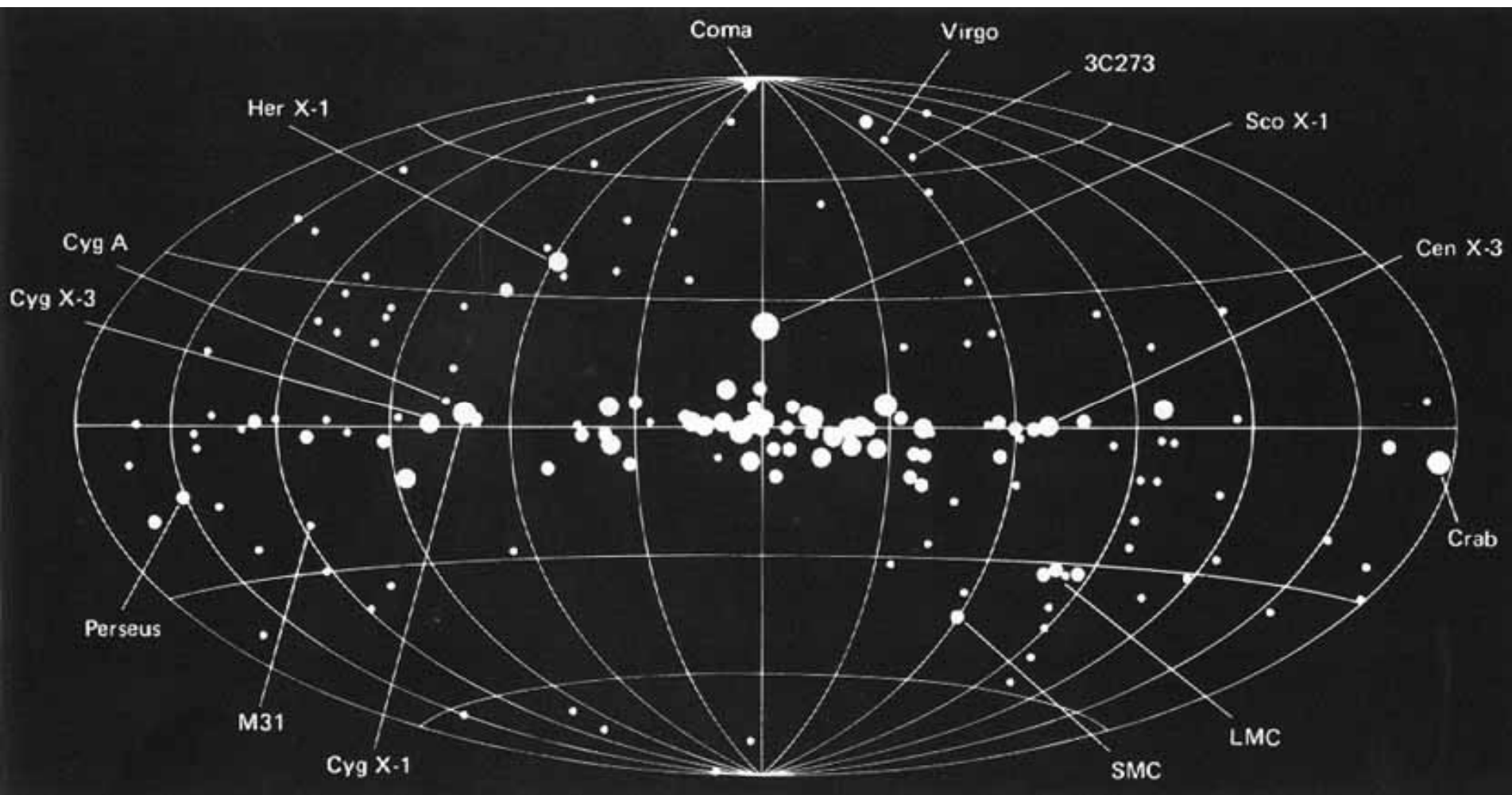
- Okresowe zmiany natężenia promieniowania
- Identyfikacja z obiektem optycznym
- Ocena masy ( $M_X > 3 M_\odot$ )
- Miękkie promieniowanie X



Fale elektromagnetyczne dochodzące z Kosmosu. Kolorem błękitnym zaznaczono obszary atmosfery, gdzie promieniowanie jest zatrzymywane na różnych wysokościach

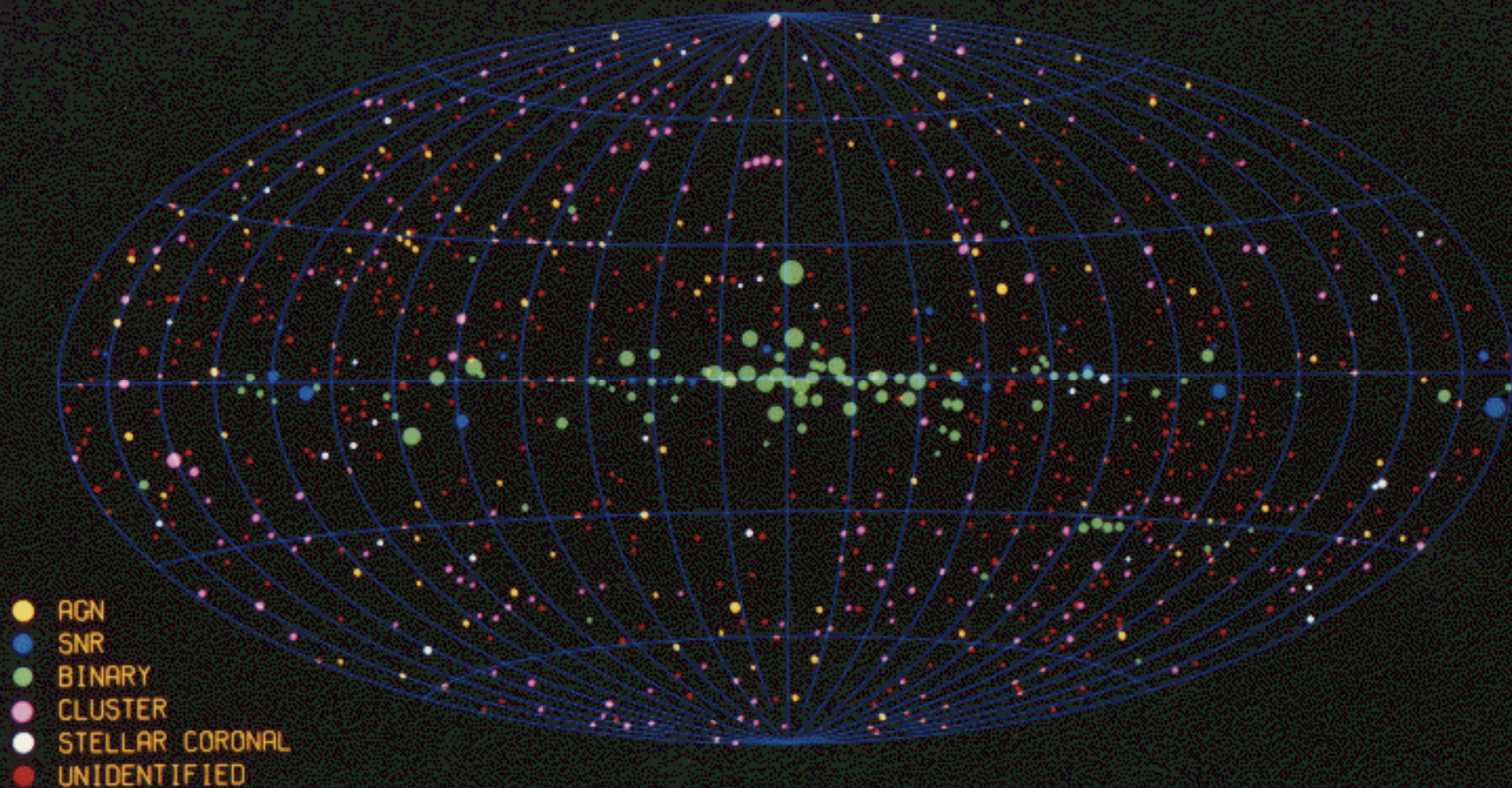


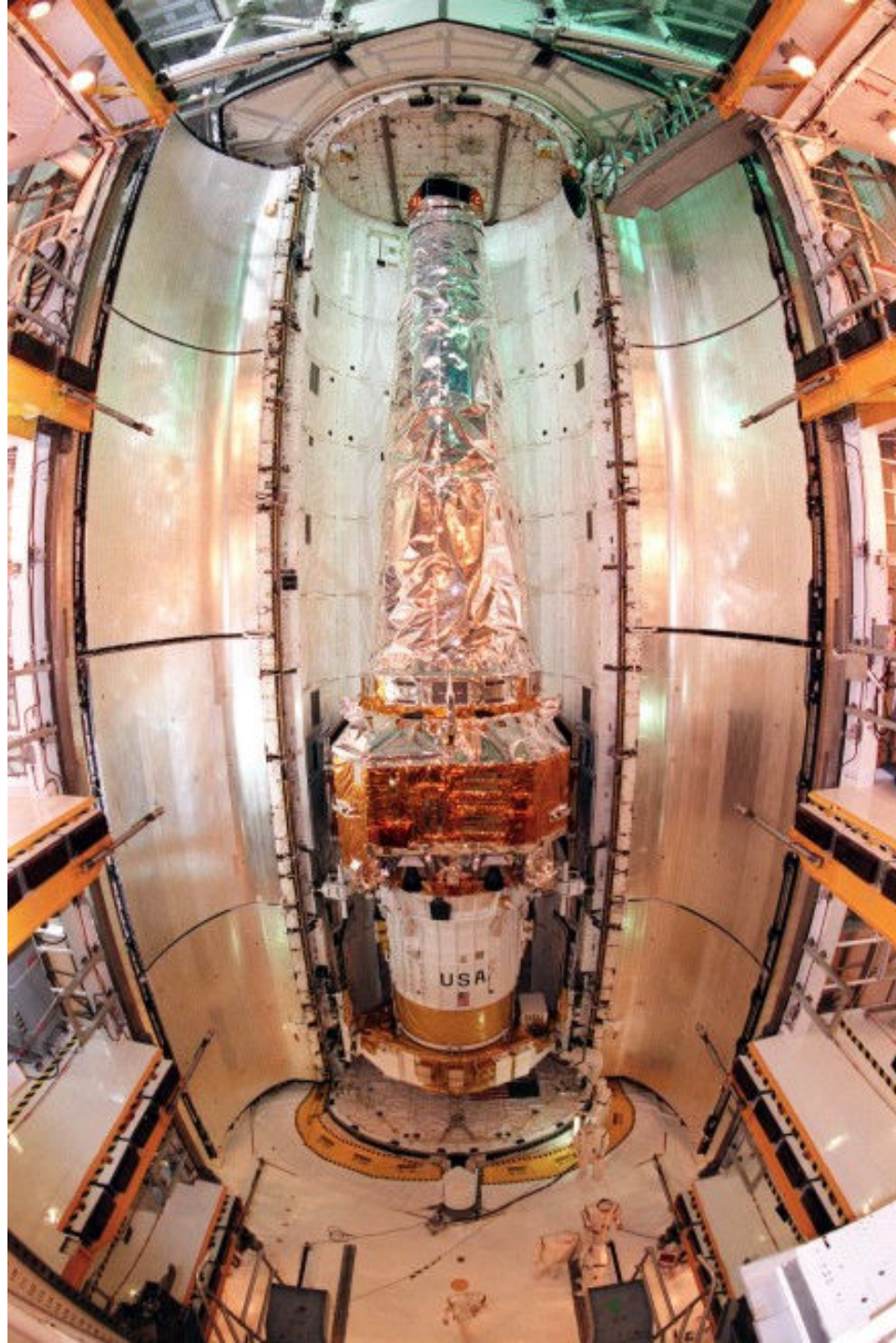


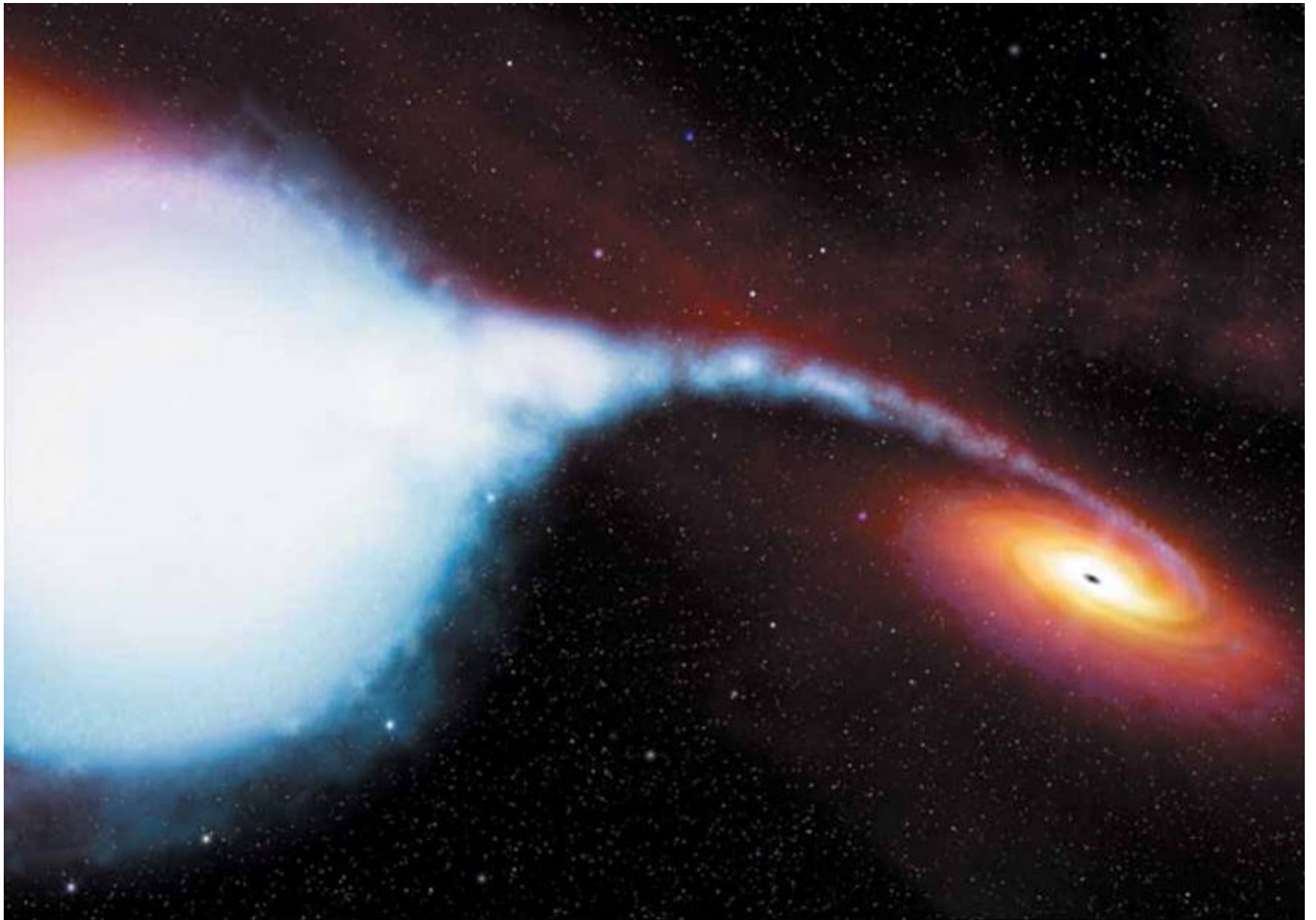


# HEAO A-1 ALL-SKY X-RAY CATALOG

NAVAL RESEARCH LABORATORY

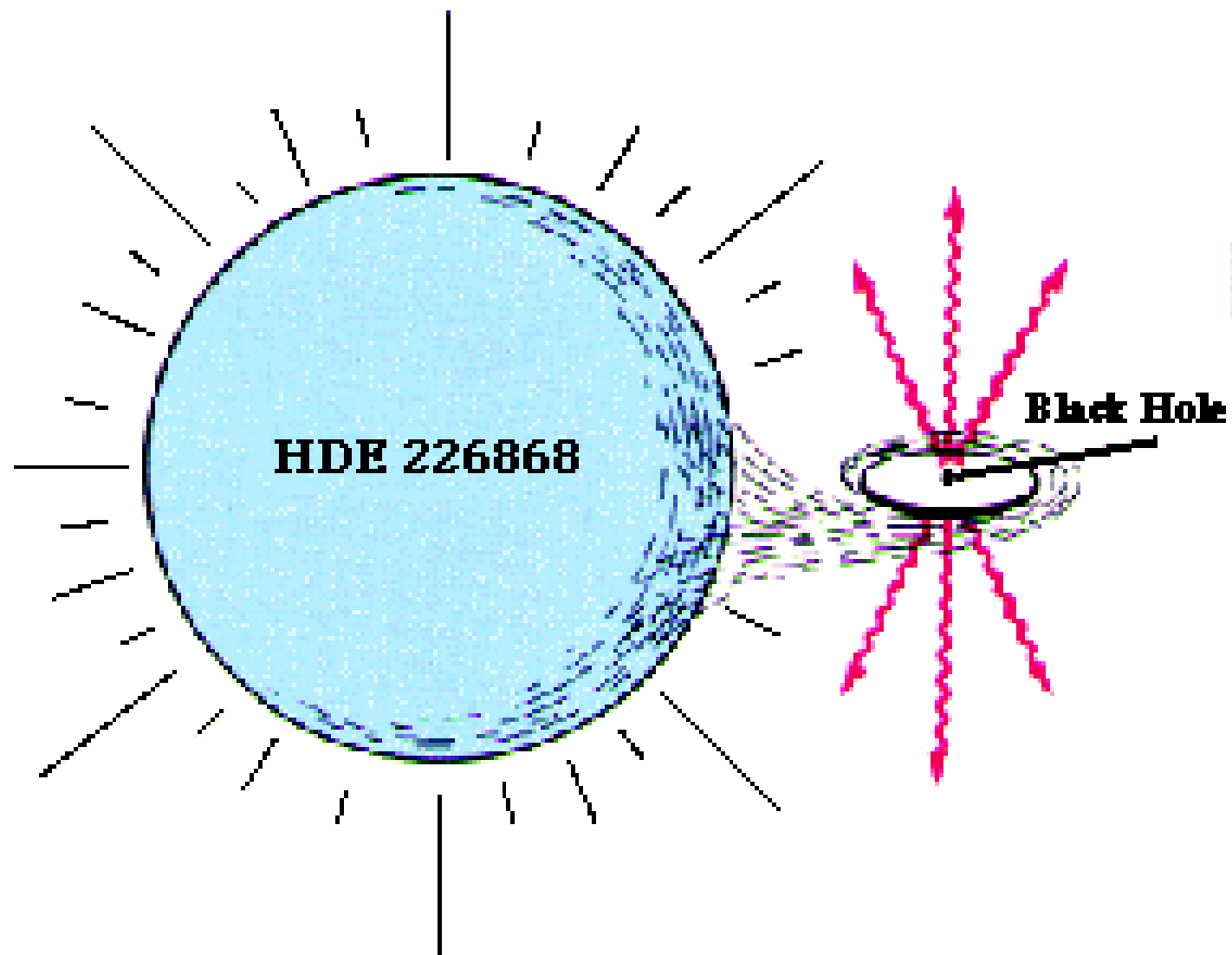


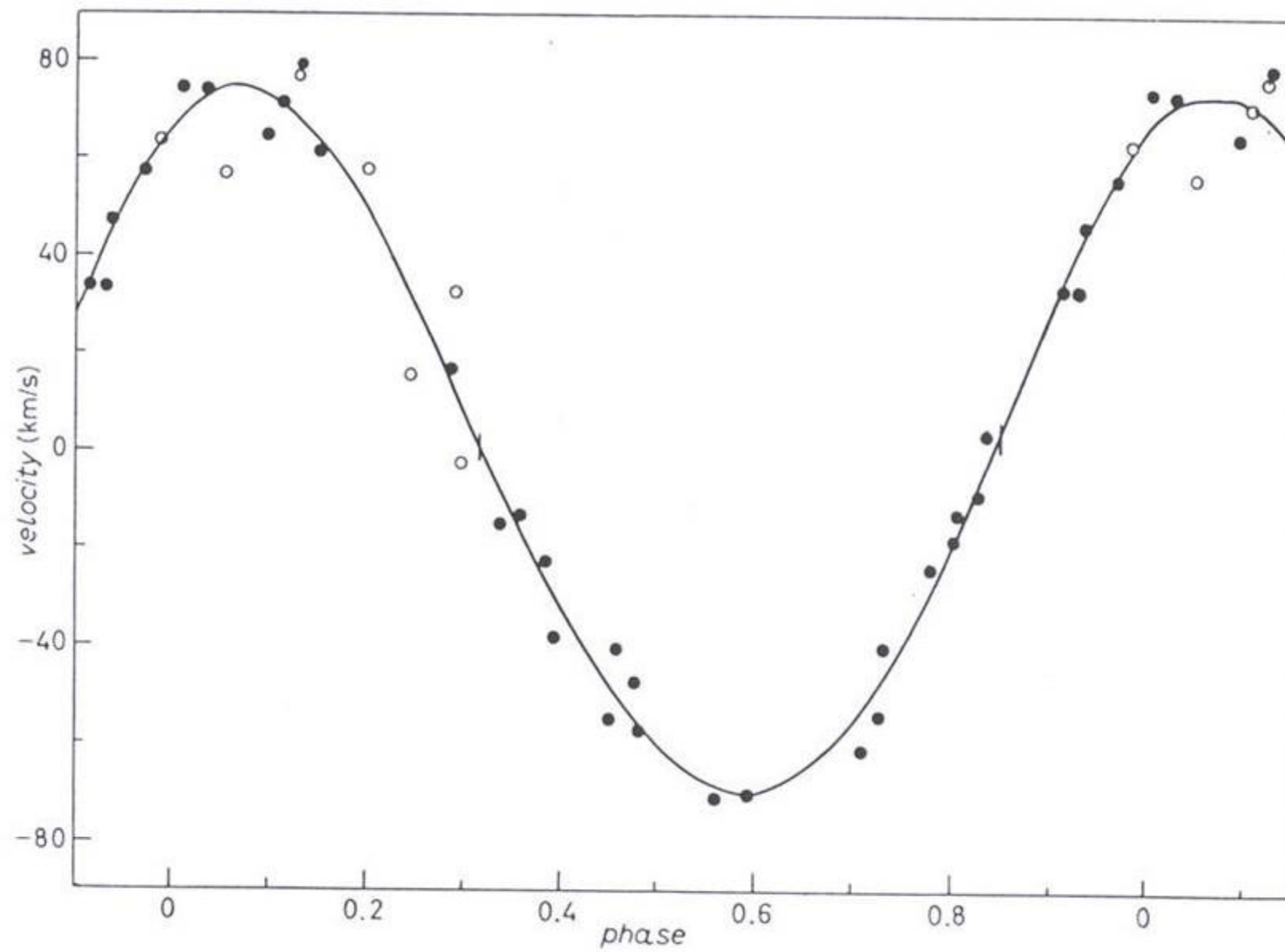




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**Fig. 14-10a, p.286**





- <sup>6</sup> Struve, O., and Sahade, J., *Publ. Astron. Soc. Pacific*, 69, 41 (1957).  
<sup>7</sup> Andrews, P. J., *Astrophys. J.*, 147, 1183 (1967).  
<sup>8</sup> Glushneva, I. N., and Esipov, V. F., *Sov. Astron. (A. J.)*, 11, 828 (1968).  
<sup>9</sup> Wade, C. M., and Hjellming, R. M., *Nature*, 235, 271 (1972).  
<sup>10</sup> Devinney, E. J., *Nature*, 233, 110 (1971).  
<sup>11</sup> Wilson, R. E., *Nature*, 234, 406 (1971).

## Position and Identification of the Cygnus X-1 Radio Source

THE initial measurements<sup>1,2</sup> of the position of the radio source associated with the X-ray source Cygnus X-1 were uncertain by 3 to 5 arc s. The results were consistent with two possible identifications with stars<sup>3</sup>: the 8.9 mag. BO1b star HDE 226868 (= BD + 34° 3815), and a 15 mag. red star 9 arc s to the north-west of the B star. Because of the apparent normality of the B star and possible signs of peculiarity in the red star<sup>3</sup>, it was not clear which should be identified with the radio source. Here, we report the resolution of the ambiguity by an accurate determination of the radio position.

The observations were made at frequencies of 2,695 and 8,085 MHz with the NRAO three-element interferometer at Green Bank from October 28 to October 31, 1971. The baseline lengths were 900, 1,800 and 2,700 m. Cygnus X-1 was observed concurrently with sixty other radio sources in a programme of precise position measurements. The method has been described previously<sup>4</sup>; certain refinements, however, were introduced in the analysis to eliminate the principal sources of systematic error. The procedures and results for the sixty sources will be described in detail later.

The position of the Cygnus X-1 radio source, with its standard errors, is found to be:

$$\alpha_{1950} = 19 \text{ h } 56 \text{ m } 28.87 \text{ s} \pm 0.02 \text{ s} \\ \delta_{1950} = +35^{\circ} 03' 55.0'' \pm 0.3''$$

The AGK2 position of HDE 226868 is

$$\alpha_{1950} = 19 \text{ h } 56 \text{ m } 28.88 \text{ s} \\ \delta_{1950} = +35^{\circ} 03' 54.9''$$

The nearly perfect positional coincidence of the radio source and the star leaves no doubt that HDE 226868 is the correct identification.

During the three-day observing period, the flux density for Cygnus X-1 was  $(12 \pm 3) \times 10^{-29} \text{ W m}^{-2} \text{ Hz}^{-1}$  at 2,695 MHz and  $(15 \pm 3) \times 10^{-29} \text{ W m}^{-2} \text{ Hz}^{-1}$  at 8,085 MHz.

It is now known<sup>5,6</sup> that HDE 226868 is a spectroscopic binary with a period of 5.6 days. Bolton<sup>6</sup> has found variable emission lines resembling those of P Cygni in high-dispersion spectra of this star. This strongly supports the identification of the radio and X-ray sources with the HDE 226868 binary.

## Identification of Cygnus X-1 with HDE 226868

THE ninth magnitude BO1b star HDE 226868 is closely coincident with the position of Cygnus X-1 and its associated variable radio source<sup>1</sup>. Dolan<sup>2</sup> has pointed out that Cyg X-1 appears to be a two component X-ray source. One component has a synchrotron spectrum, and the other has a thermal (or bremsstrahlung) spectrum. The latter component varies on a time scale of days in a way that suggests it is being eclipsed. Therefore I decided to take photographic spectra of HDE 226868 to look for velocity and spectrum variations that might be correlated with the X-ray fluctuations. I find that the velocity of the star varies with a period consistent with that of the X-ray variation. It may not be possible, however, to interpret the X-ray variations in terms of simple eclipses.

The spectrograms were taken between mid-September and mid-November 1971 with the 74-inch telescope of the David Dunlap Observatory in Richmond Hill, Ontario. All except one were taken at a dispersion of  $12 \text{ \AA mm}^{-1}$ , but because of the star's faintness and unfavourable weather conditions it was necessary to use projected slit widths of 40 to 50  $\mu\text{m}$ . These observations have been supplemented by results from 5 to 40  $\text{\AA mm}^{-1}$  plates taken in one night with the 90-inch reflector of the Steward Observatory of the University of Arizona. These plates were obtained and measured by Dr Roberta Humphreys, who communicated the results to us before publication. She also provided some additional observations of emission features in the spectrum, and Mr David L. DuPuy of the David Dunlap Observatory obtained UVB photometry of HDE 226868 on three nights.

The results of the radial velocity measures are given in Table 1 and the velocity curve is plotted in Fig. 1 for a period

Table 1 Radial Velocity Measurements

Julian date	$V_r$ (km s <sup>-1</sup> )	Standard deviation (km s <sup>-1</sup> )	Inter- stellar K-line (km s <sup>-1</sup> )	H $\beta$ emission (km s <sup>-1</sup> )	Disper- sion ( $\text{\AA mm}^{-1}$ )
*2441210.660	+15	$\pm 9$	-19.5		43
1213.665	-24	$\pm 9$	-15.7	+176	12
†1217.588	-58	$\pm 10$	-14.3	+39	12
			+74.7		
1224.581	-41	$\pm 7$	-10.7	+154	12
1225.696	+33	$\pm 9$	-15.6		12
1237.579	+57	$\pm 15$	-28.3		12
1245.555	-48	$\pm 14$	-12.6		12
1252.549	-62	$\pm 9$	-15.6		12
1259.524	+56	$\pm 7$	-14.4		12
1261.573	-15	$\pm 8$	-17.2		12
‡1263.7	-65	$\pm 6$			40

\* Unidentified emission feature at 124510.10  $\text{\AA}$

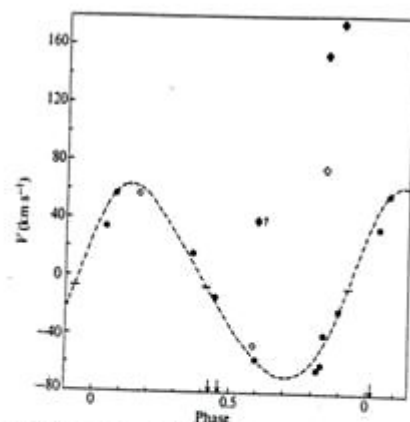


Fig. 1 The radial velocity of HDE 226868 plotted against phase for a 5.607 day period. The circles denote the B star velocities. Open diamonds indicate uncertain measures. The solid diamonds indicate H $\beta$  emission line velocities, and the open diamonds indicate the secondary component of the K-line measured on one plate. Horizontal tick marks on the velocity curve indicate the centre of mass velocity and therefore the expected eclipse positions. The arrows indicate phases at which photometry was obtained by DuPuy.

of 5.607 days. The orbital elements in Table 2 were derived from this velocity curve. The velocity curve has several notable features. In particular the absorption and emission lines near phase of 0.9 indicate that there is a gas stream moving from the B star toward the unseen companion. The emission line profile is flat-topped suggesting that the feature is a blend of sharper lines having a velocity range of +75 to +350 km s<sup>-1</sup> relative to the B star.

The large velocity variation indicates that the ratio of the masses,  $M_1/M_2$ , of the two stars in the system cannot be very large. The mass function

$$f(M) = \frac{M_2^3 \sin^3 i}{(M_1 + M_2)^2} = 0.16$$

requires that  $M_2 > 3M_\odot$  if  $M_1 \geq 12 M_\odot$ . I believe that the latter number is a reasonable lower limit on the mass of the B star. A star could come to have a BOIb spectrum in three ways. The first is through normal stellar evolution, in which case the expected mass would be 12 to 15  $M_\odot$ . The second and third are through mass exchange in a binary system<sup>3</sup>. In the first of these cases a star more massive than 12 to 15  $M_\odot$  could start to exchange mass before the onset of helium burning. Such a star would evolve downwards in the H-R diagram to the right of the main-sequence and could at some point have a BOIb spectrum. It would still have at least 12 to 15  $M_\odot$  at that point, however. A 12 to 15  $M_\odot$  star evolving by mass exchange as above might also have a BOIb spectrum after it had lost 75–80% of its mass. Such a star should show pronounced spectral anomalies, which are not observed in HDE 226868. I believe, therefore, that 12  $M_\odot$  and 3  $M_\odot$  are

Table 2 Preliminary Orbital Elements for HDE 226868

$P = 5.607$ days	$T = 2441214.241$
$V_0 = -7.5$ km s <sup>-1</sup>	$T^* = 2441216.554$
$K = 66$ km s <sup>-1</sup>	$T^\dagger = 2441219.472$
$e = 0.14$	$a \sin i = 5 \times 10^6$ km = 7.2 $R_\odot$
$\omega = 299^\circ$	$f(M) = 0.16$

\* Unseen companion in front of B star.

† Unseen companion behind B star.

reasonable lower limits on the primary and secondary masses, respectively.

The crucial point in identifying HDE 226868 with Cyg X-1 is the comparison of the X-ray period with the velocity period. The radial velocity observations will permit any period within the range 5.595 to 5.635 days. Unfortunately the X-ray data are not so restrictive. Any determination of the X-ray periodicity depends heavily on the minima. At present there are only six well-determined minima in the seven year span of observations. The shortest separation between minima is approximately 6 days so that periods shorter than this cannot be conclusively rejected. Furthermore, the discrete points give no information about the length of the minima, and this permits some leeway in fitting a period to the observations.

Because of these difficulties I have chosen to look for a period within the range allowed by the radial velocities that would fit the X-ray data, rather than to try to determine an independent period for the X-ray data. I have adopted Dolan's interpretation<sup>2,4</sup> of the X-ray data except for two observations which I explain below. I have also added three data points reported by Matteson<sup>5</sup>.

I have chosen to place in the uncertain category a point that Dolan called a maximum<sup>2</sup> and another that he called a minimum<sup>4</sup>. The first of these was a point obtained by Brini *et al.*<sup>6</sup> which was the average of observations on two separate days. The second observation would fall very near a minimum for the period I adopt, and the error bars on the mean of the two observations are large. Therefore I suspect that a maximum and a minimum may have been averaged and the point should be regarded as uncertain. The second observation that I regard as uncertain is one by Agrawal *et al.*<sup>7</sup> that Dolan interpreted as showing the onset of an eclipse near the end of a 3 h observational run. But Cyg X-3 was also in the field of the detector at the time of the decline. The interpretation of the decline depends on the relative intensity of Cyg X-1 and Cyg X-3. Because no independent information regarding the intensity of the variable source Cyg X-3 is available, this observation should be regarded as uncertain.

I find that a period of 5.607 days fits the X-ray and radial velocity data very well. The X-ray data are plotted against phase for this period in Fig. 2. All but one of the minima fall near primary eclipse (unseen companion in front of B star) and the other minimum is near secondary eclipse (unseen companion behind B star). From the relationship of the X-ray and velocity data it seems that primary eclipse occurs when the unseen companion occults the X-ray region. If the minimum at phase 0.03 is a real eclipse, then its position combined with that of the primary eclipse indicates that the X-ray source is near the unseen companion but trails behind it in the orbit and lies somewhat inside the orbit. More information about the reality and length of secondary eclipse would allow some limits to be placed on the radius of the secondary. Unless the inclination of the orbit is small, the unseen companion cannot be very large because the photometry near primary eclipse (arrows in Fig. 1) indicates that there is no optical eclipse.

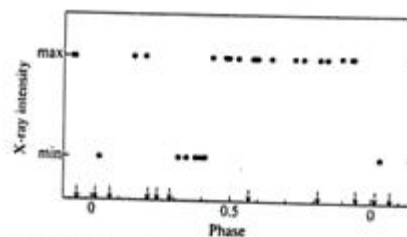


Fig. 2 The X-ray observations plotted against phase for a 5.607 day period. Observations were classified as maximum, minimum, or uncertain. The phases of the uncertain observations are indicated by arrows.

The motion of the gas stream and the apparent position of the X-ray source strongly suggest that the X-rays are being produced through the interaction of the gas stream and the unseen companion. The high energies of the X-rays imply that large accelerations are involved—accelerations such as might be produced by the intense gravitational field of a collapsed object. The lower limits placed on the secondary mass are too high for a white dwarf and probably rule out a neutron star. The lack of a supernova remnant also argues against the secondary being a neutron star. This raises the distinct possibility that the secondary is a black hole. Further observations around secondary eclipse could test this possibility.

The good agreement between the velocity variations of HDE 226868 and the X-ray variations of Cyg X-1, combined with their close positional coincidence, argues strongly for their identity. Furthermore, I have found  $\lambda 4686$  of HeII in emission on plates taken by Humphreys, and this and other emission lines may be marginally visible on my plates. This would be very unusual for a BO1b star, but  $\lambda 4686$  has been seen in emission in the spectra of Sco X-1 (ref. 8) and Cyg X-2 (ref. 9). Thus the identity of Cyg X-1 and HDE 226868 appears almost certain.

Several problems remain, however. I have already discussed the problems involved in deriving a period for the X-ray variations. The observations by Matteson<sup>3</sup> suggest that an additional complication may be present. He finds that Cyg X-1 varies by a factor of seven while the observations summarized by Dolan<sup>2,4</sup> indicate variations of no more than a factor of two. The difference here may be due to some of the experimental problems discussed by Dolan<sup>2</sup>. The difference might also be caused by variations in the synchrotron component of the source. If this were the case, it would be quite easy to derive a spurious period for the X-ray variations from the limited data that are currently available. The true nature of the X-ray variation can only be adequately determined by continuous monitoring of Cyg X-1 over a large energy range. Ideally this should be coordinated with optical and radio observations.

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- <sup>1</sup> Braes, L. L. E., and Miley, G. K., *Nature*, **232**, 246 (1971).
- <sup>2</sup> Dolan, J. F., *Space Sci. Rev.*, **10**, 830 (1969).
- <sup>3</sup> Plavec, M., *Pub. Astron. Soc. Pacific*, **82**, 937 (1970).
- <sup>4</sup> Dolan, J. F., *Nature*, **233**, 109 (1971).
- <sup>5</sup> Matteson, J. L., *Bull. Amer. Astron. Soc.*, **3**, 456 (1971).
- <sup>6</sup> Brini, D., Cirigli, U., Fuligni, F., Moretti, E., and Vespignani, G., *Astrophys. J.*, **149**, 429 (1967).
- <sup>7</sup> Agrawal, P. C., Gokhale, G. S., Iyengar, V. S., Kunte, P. K., Manchanda, R. K., and Sreekantan, B. V., *Nature*, **232**, 38 (1971).
- <sup>8</sup> Hiltner, W. A., and Mook, D., *Ann. Rev. Astron. Astrophys.*, **8**, 139 (1970).
- <sup>9</sup> Kraft, R. P., and Demoulin, M., *Astrophys. J. Lett.*, **150**, L83 (1967).

sources, Braes and Hovenier<sup>4</sup> predicted that X-ray emission might be observable from the region of Per OB2. Such an X-ray source, 2ASE 0352+30, has now been detected (R. Giacconi *et al.*, unpublished catalogue of Uhuru X-ray sources). The quoted Uhuru position of this source, which has a  $2\sigma$  uncertainty of  $5' \times 15'$ , agrees to within  $2'$  with that of X Per. These arguments lead us to believe that the X-ray source is associated with this star.

Because some other X-ray sources are known to be radio emitters, we have searched for 1,415 MHz radiation from the X Per region with the Westerbork synthesis radio telescope. Twelve-hour observations made on both May 24 and 27, 1971, failed to detect any source brighter than 0.005 flux units within the 2ASE 0352+30 error box. Because of the extreme radio variability of X-ray sources, however, these measurements are not conclusive. Continued monitoring of X Per at both optical and radio wavelengths is needed.

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Leiden 2401,  
The Netherlands

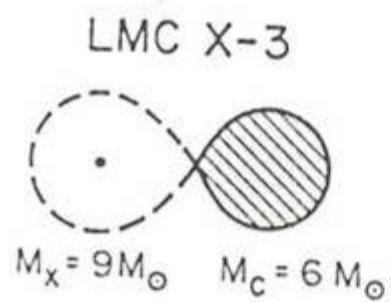
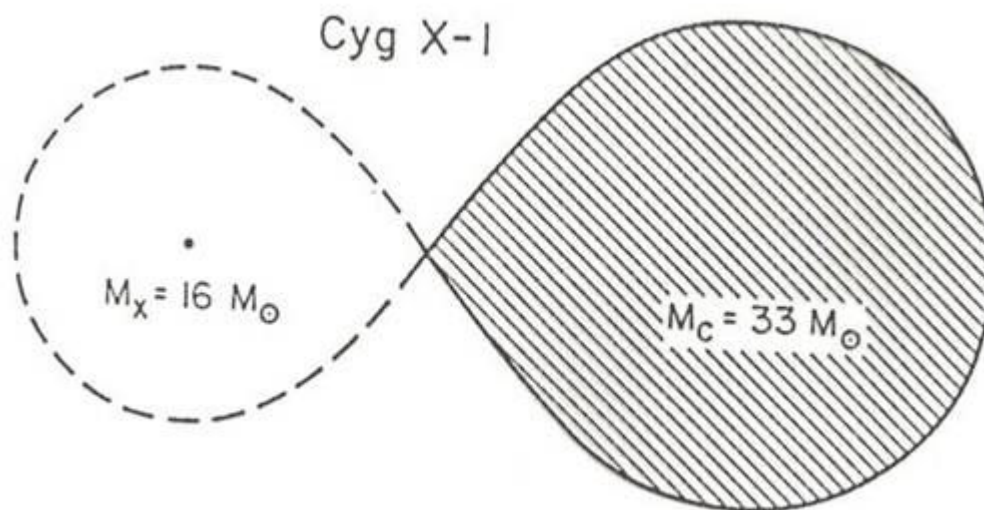
Received December 21, 1971.

- <sup>1</sup> Borgman, J., and Blaauw, A., *Bull. Astron. Insts. Netherlands*, **17**, 358 (1964).
- <sup>2</sup> Kukarkin, B. V., Kholopov, P. N., Efremov, Yu. N., Kukarkina, N. P., Kurochkin, N. E., Medvedeva, G. I., Perova, N. B., Fedorovich, V. P., and Frolov, M. S., *General Catalogue of Variable Stars*, **2**, third edition (Moscow, 1970).
- <sup>3</sup> Blaauw, A., *Bull. Astron. Insts. Netherlands*, **15**, 265 (1961).
- <sup>4</sup> Braes, L. L. E., and Hovenier, J. W., *Nature*, **209**, 360 (1966).

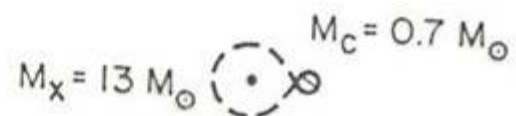
## Possible Identification of X Persei with an X-ray Source

COMPARISON of the Yale catalogue<sup>1</sup> with a recent catalogue of 116 X-ray sources observed with the Uhuru satellite (private communication from R. Giacconi, H. Gursky, E. Kellogg, S. Murray, E. Schreier and H. Tananbaum) shows that the position of the irregular variable star X Persei (see Table 1) coincides with that of the X-ray source 2ASE 0352+30. The total number of chance coincidences of bright stars to within 0.5 arc min in  $\alpha$  and  $0^\circ.1$  in  $\delta$  of the Uhuru X-ray source positions is estimated to be  $\sim 1$ —the exact number of chance coincidences is difficult to evaluate because both the bright stars and the X-ray sources have a non-random distribution on the sky—but the very unusual nature of X Persei lends some support to the speculation that the positional agreement of this star with an X-ray source may not be a chance coincidence. The spectrum of X Persei is classified as O pe, and is peculiar because it is strongly veiled.

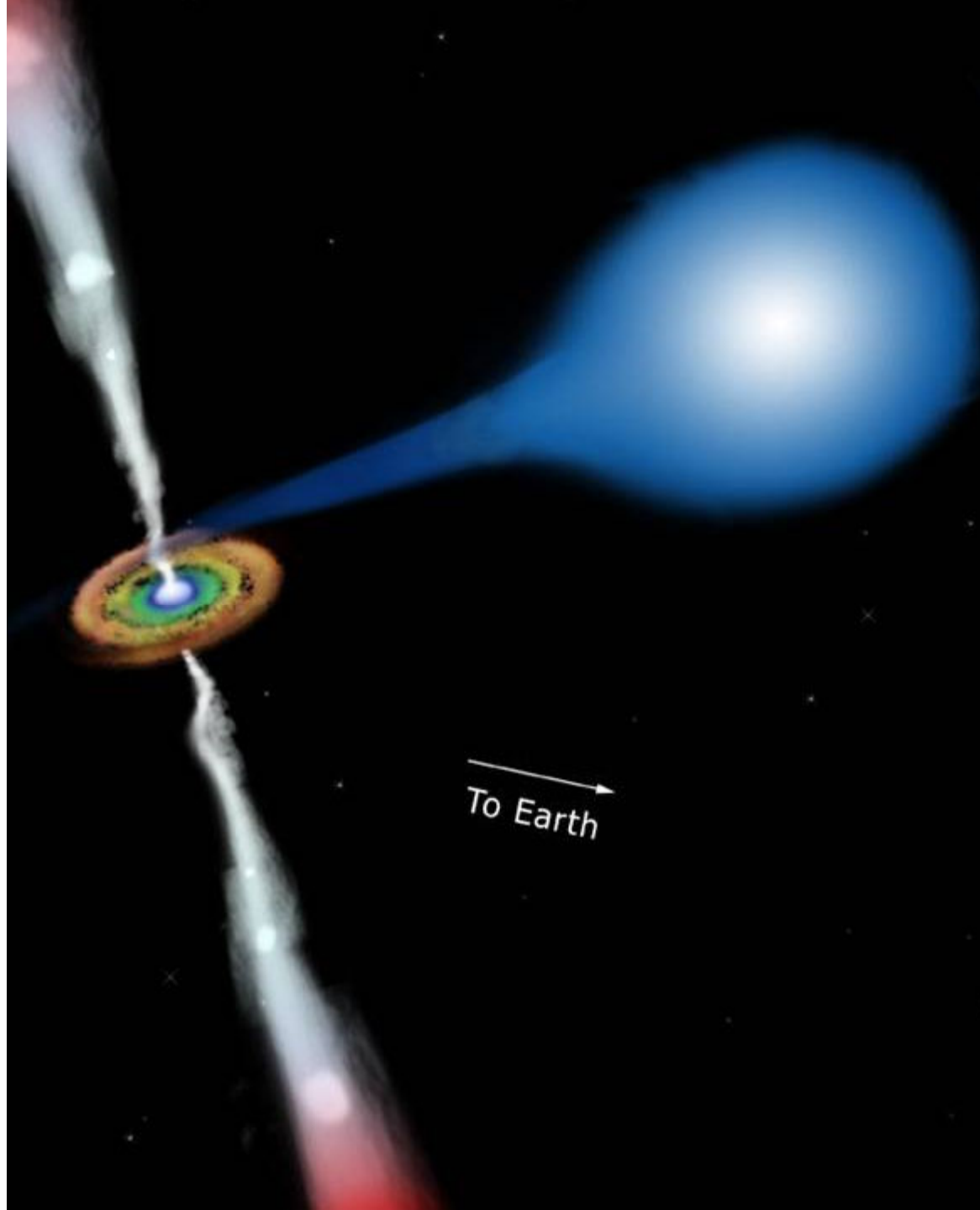
Table 1 Comparisons of the Positions of X Persei and 2ASE 0352+30.



A0620-00



Object	X-ray luminosity ( $\text{erg s}^{-1}$ )	Distance (kpc)	Spectral type	V	Orbital period (days)	$K$ velocity ( $\text{km s}^{-1}$ )	Mass function ( $M_{\odot}$ )	Mass ( $M_{\odot}$ )
Cyg X-1	$2 \times 10^{37}$	2.5	O9.7I	9	5.6	76	0.25	$>3$
LMC X-3	$3 \times 10^{38}$	55	B3V	17	1.7	235	2.3	$>6$
A0620-00	$1 \times 10^{38}$	1	K5V	12-18	0.32	457	2.91	$>3$
V404 Cyg	$2 \times 10^{39}$	4	K0	13-19	6.5	210	6.3	$>6$



# Neutron stars

1.4  $M_{\odot}$

PSR2127+11C (C)  
 PSR2127+11C (P)  
 PSR2302+46 (C)  
 PSR2302+46 (P)  
 PSR1802-07 (P)  
 PSR1855+09 (P)  
 PSR1534+12 (C)  
 PSR1534+12 (P)  
 PSR1913+16 (C)  
 PSR1913+16 (P)  
 4U1700-37  
 4U1538-52  
 Her X-1  
 Vela X-1  
 SMC X-1  
 LMC X-1  
 Cen X-3  
 Cen X-4

# Black holes

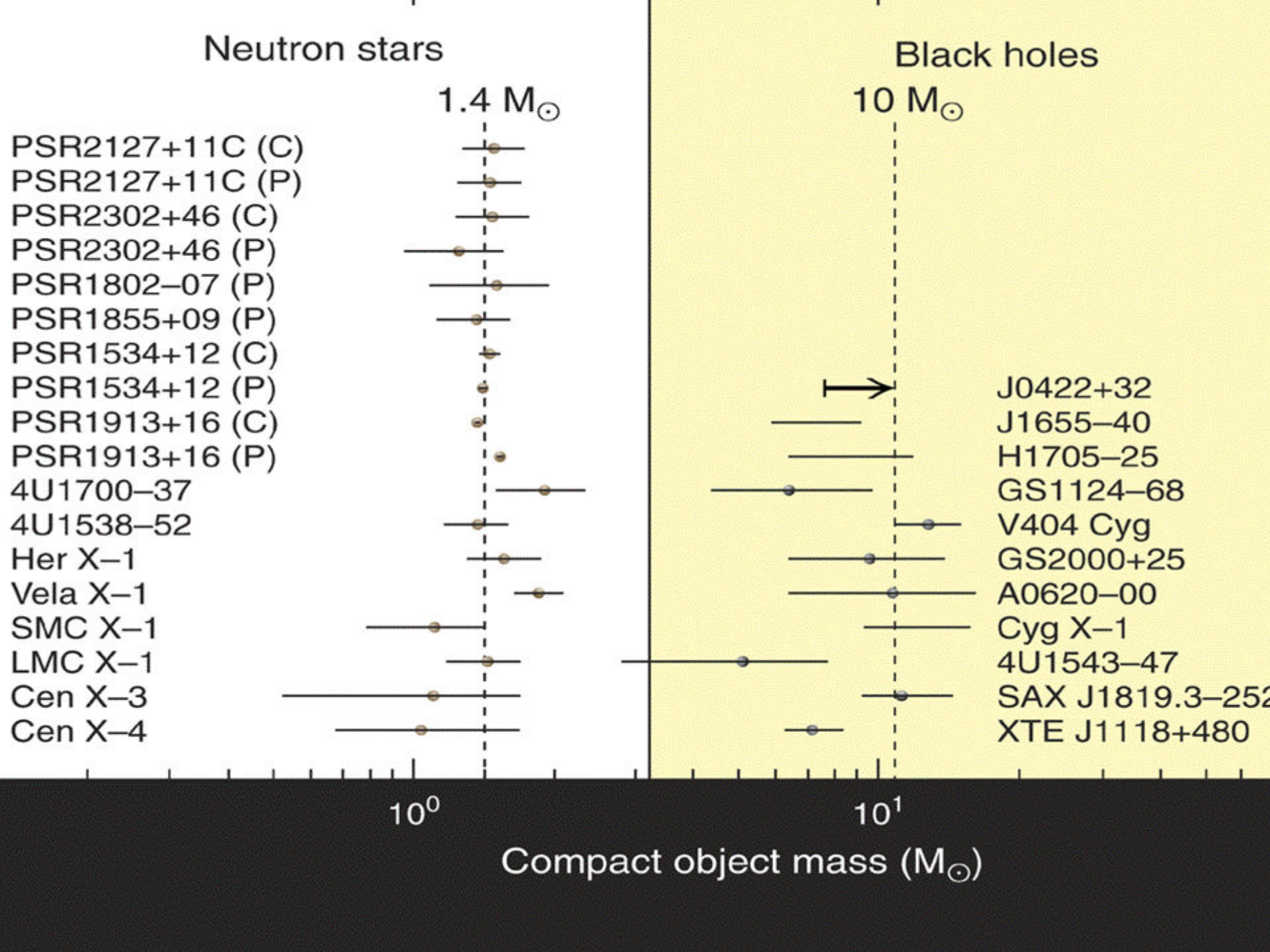
10  $M_{\odot}$

J0422+32  
 J1655-40  
 H1705-25  
 GS1124-68  
 V404 Cyg  
 GS2000+25  
 A0620-00  
 Cyg X-1  
 4U1543-47  
 SAX J1819.3-252  
 XTE J1118+480

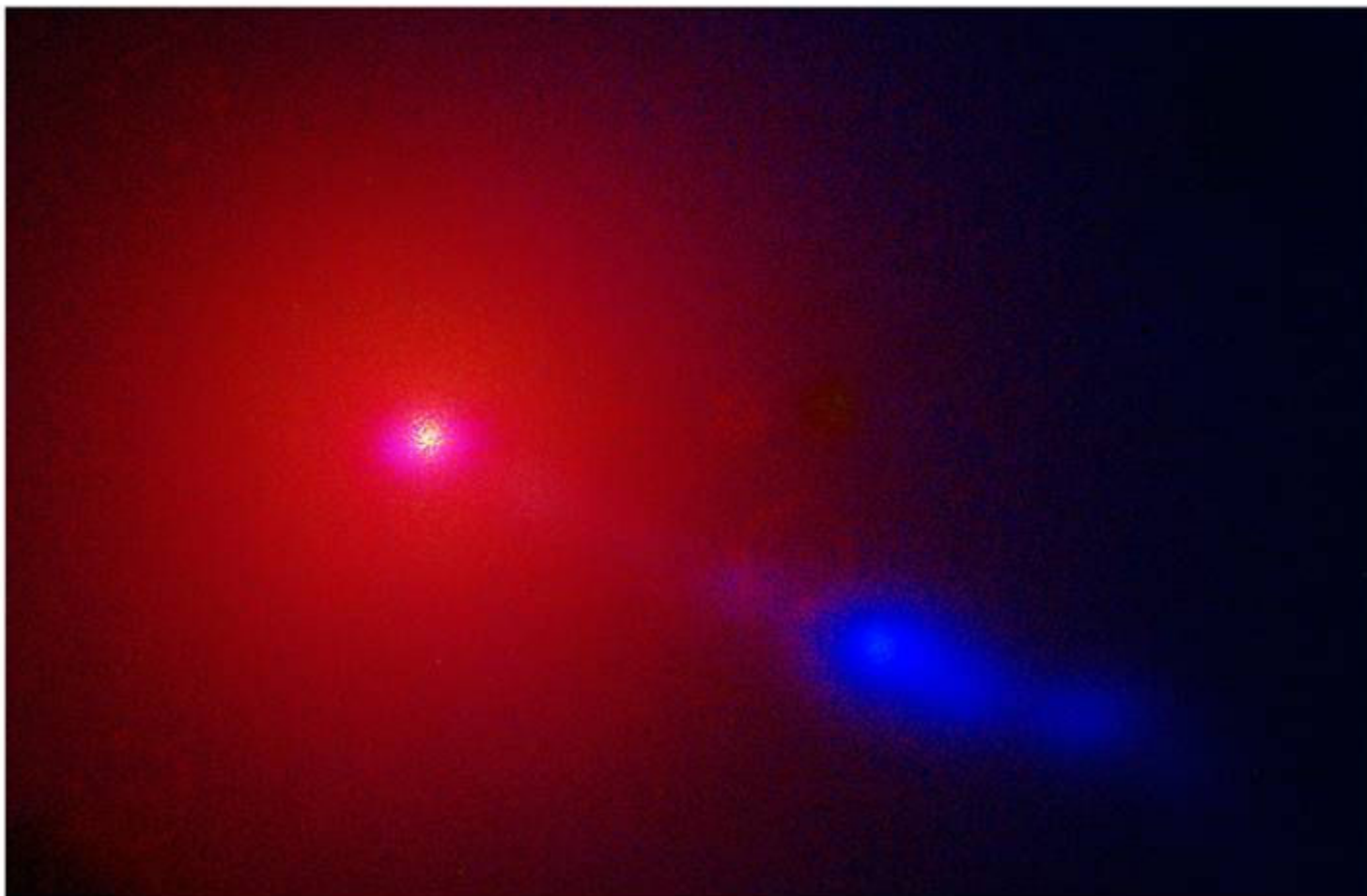
$10^0$

$10^1$

Compact object mass ( $M_{\odot}$ )





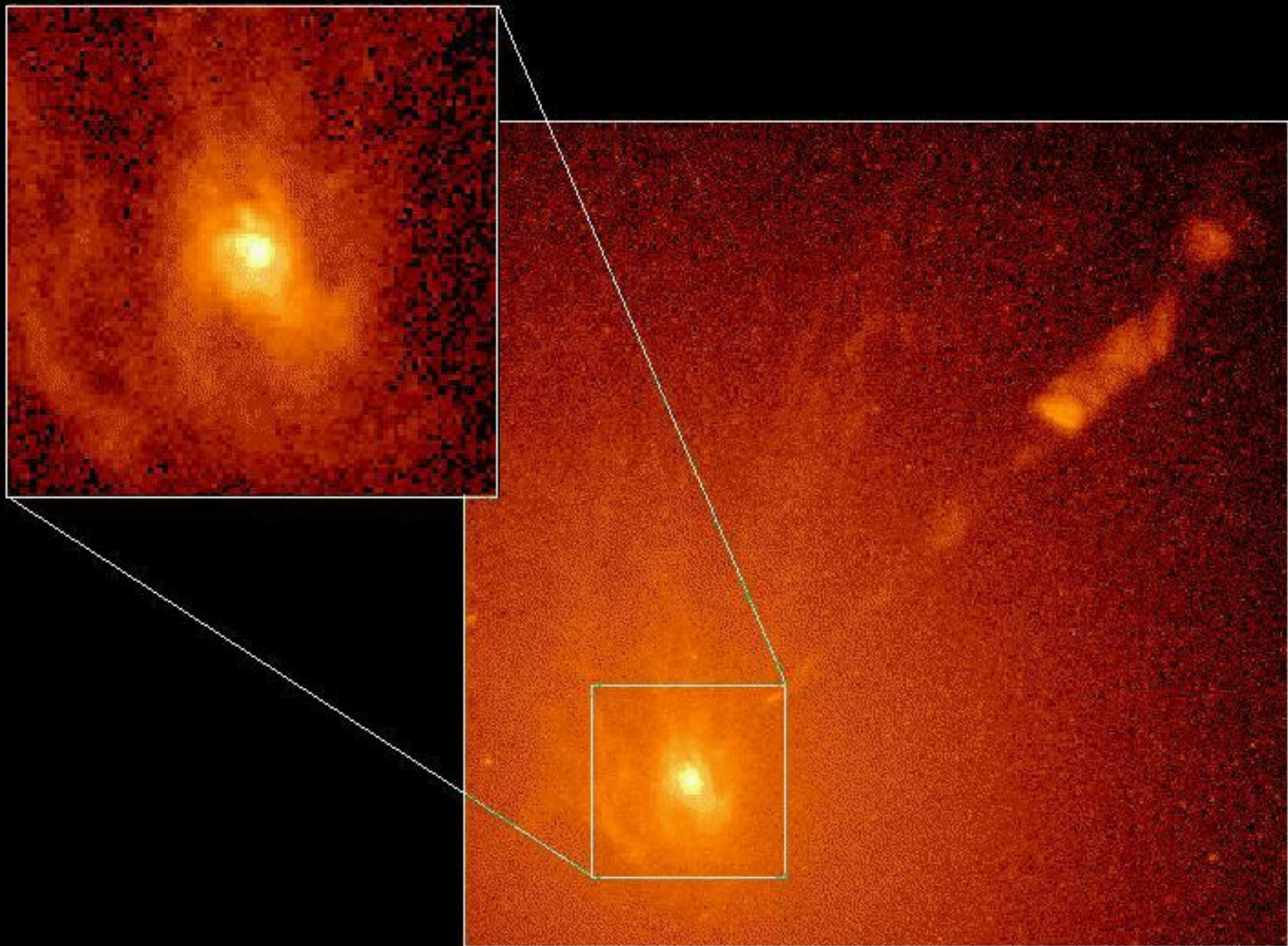


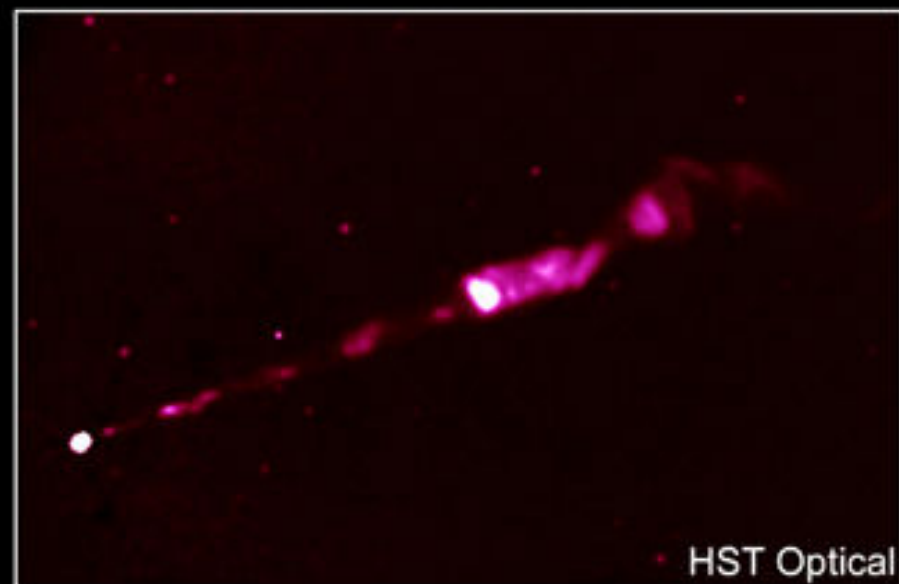
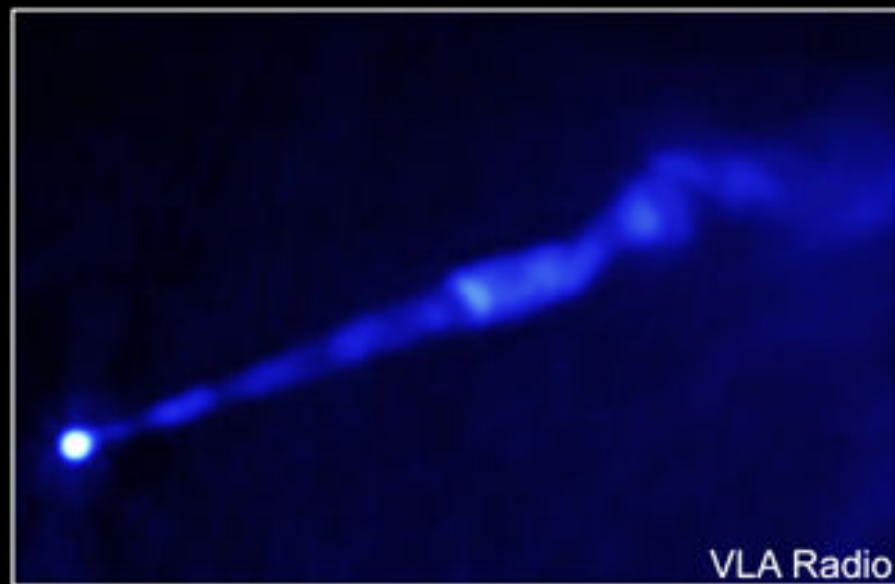
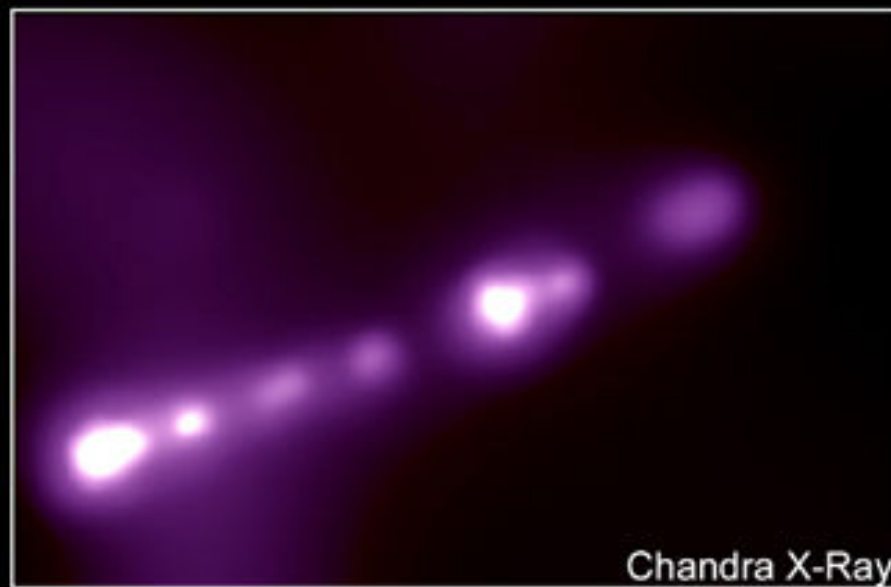
The Energetic Jet in Messier 87

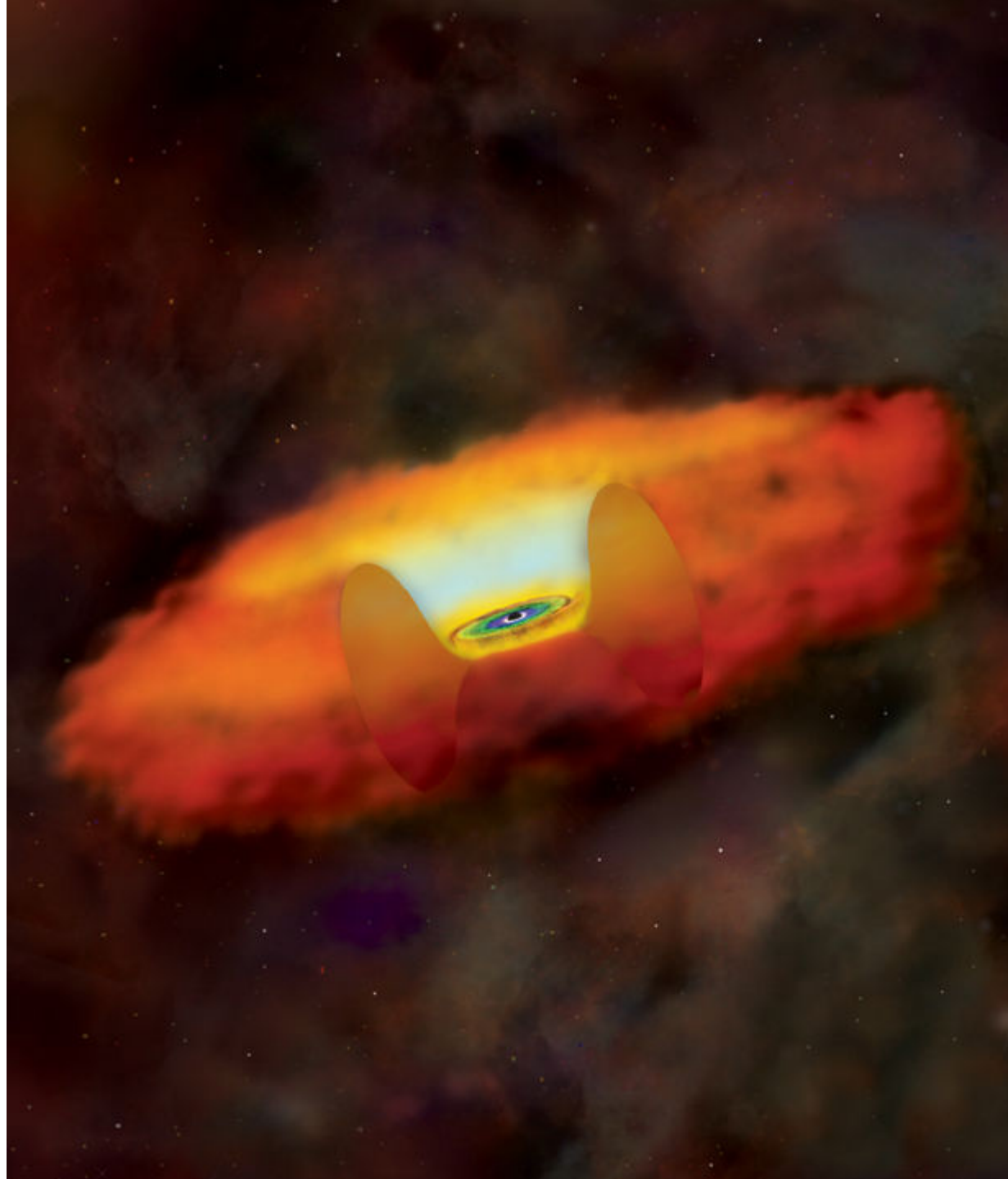
VLT UT1 First Light Photo No.7

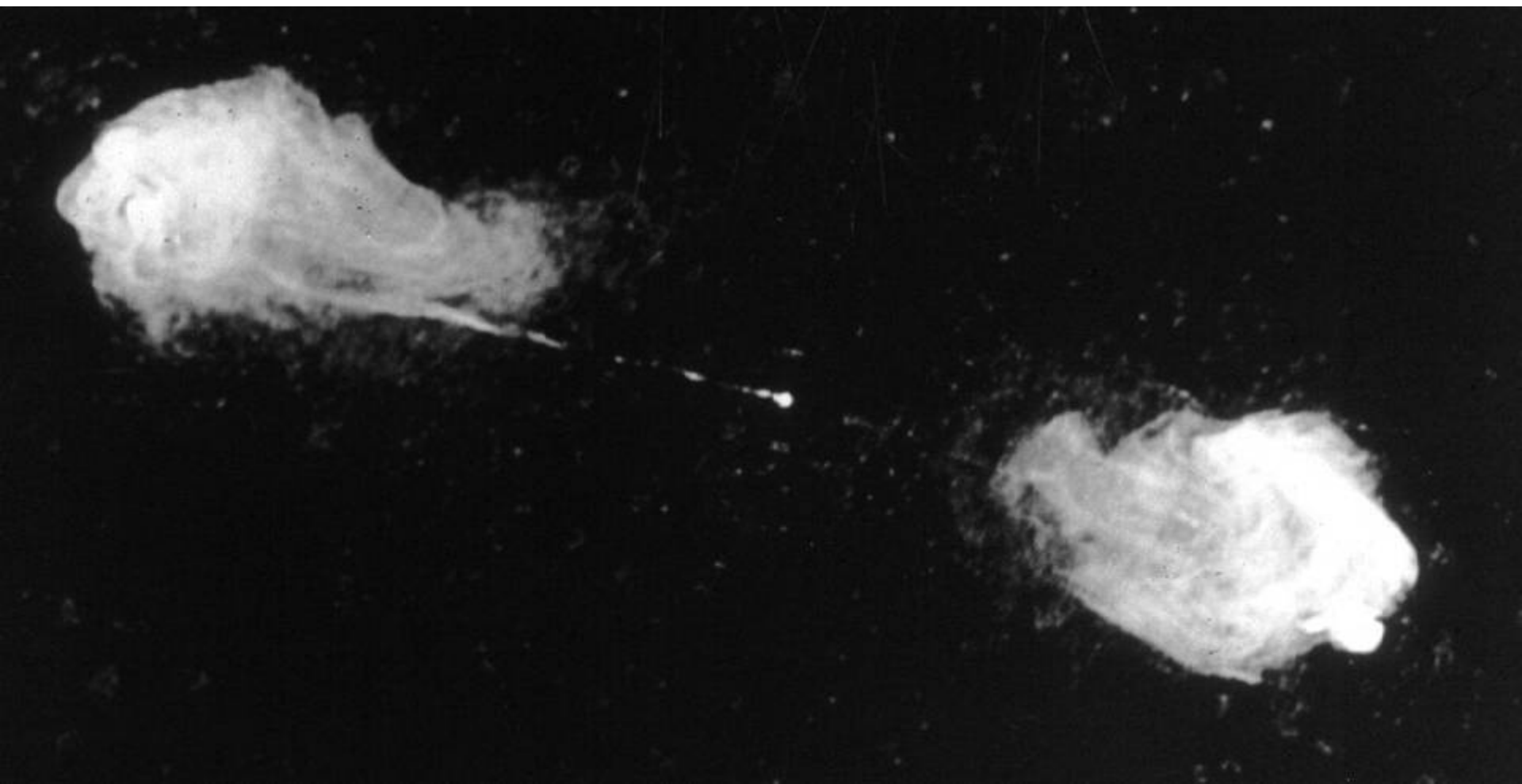
European Southern Observatory



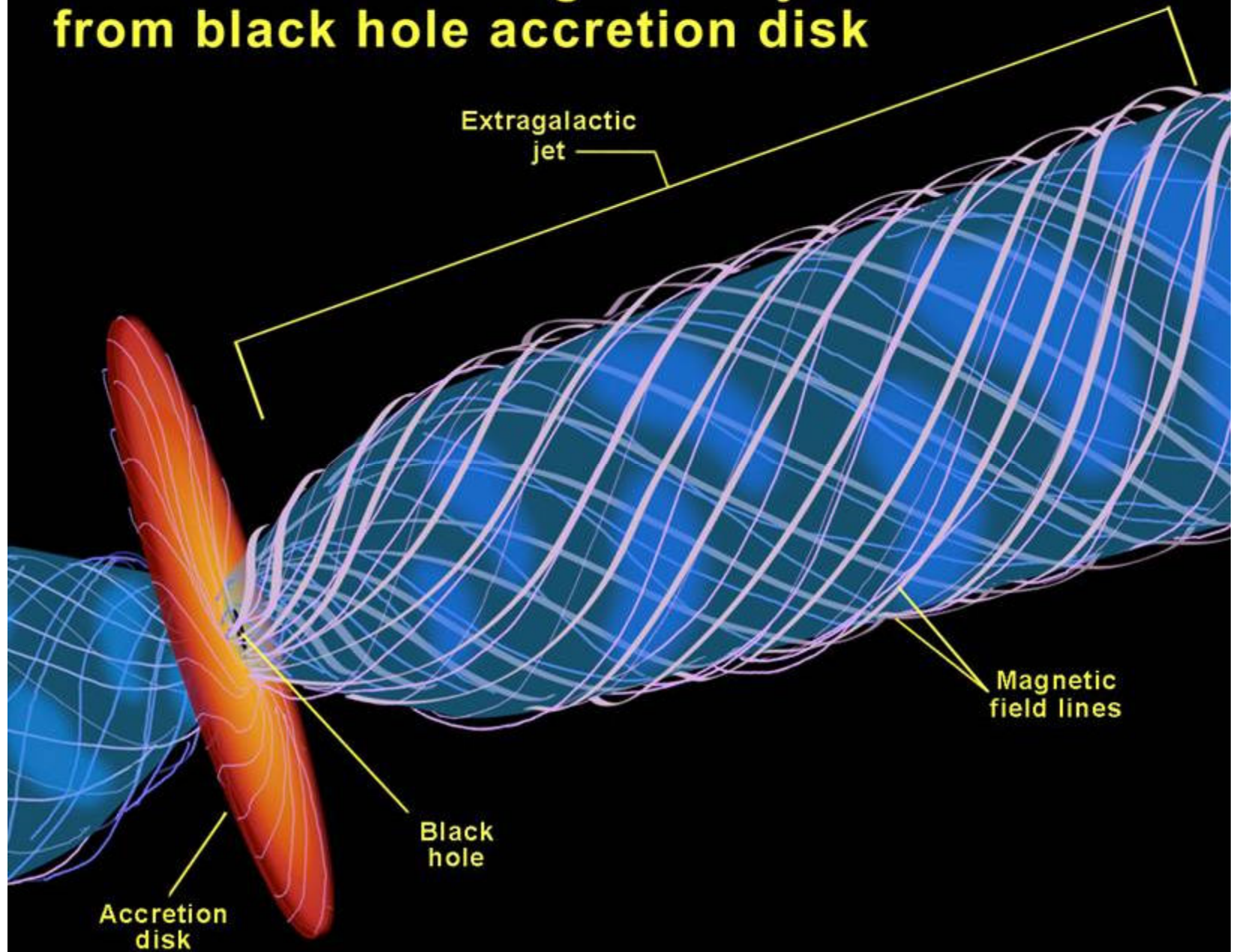


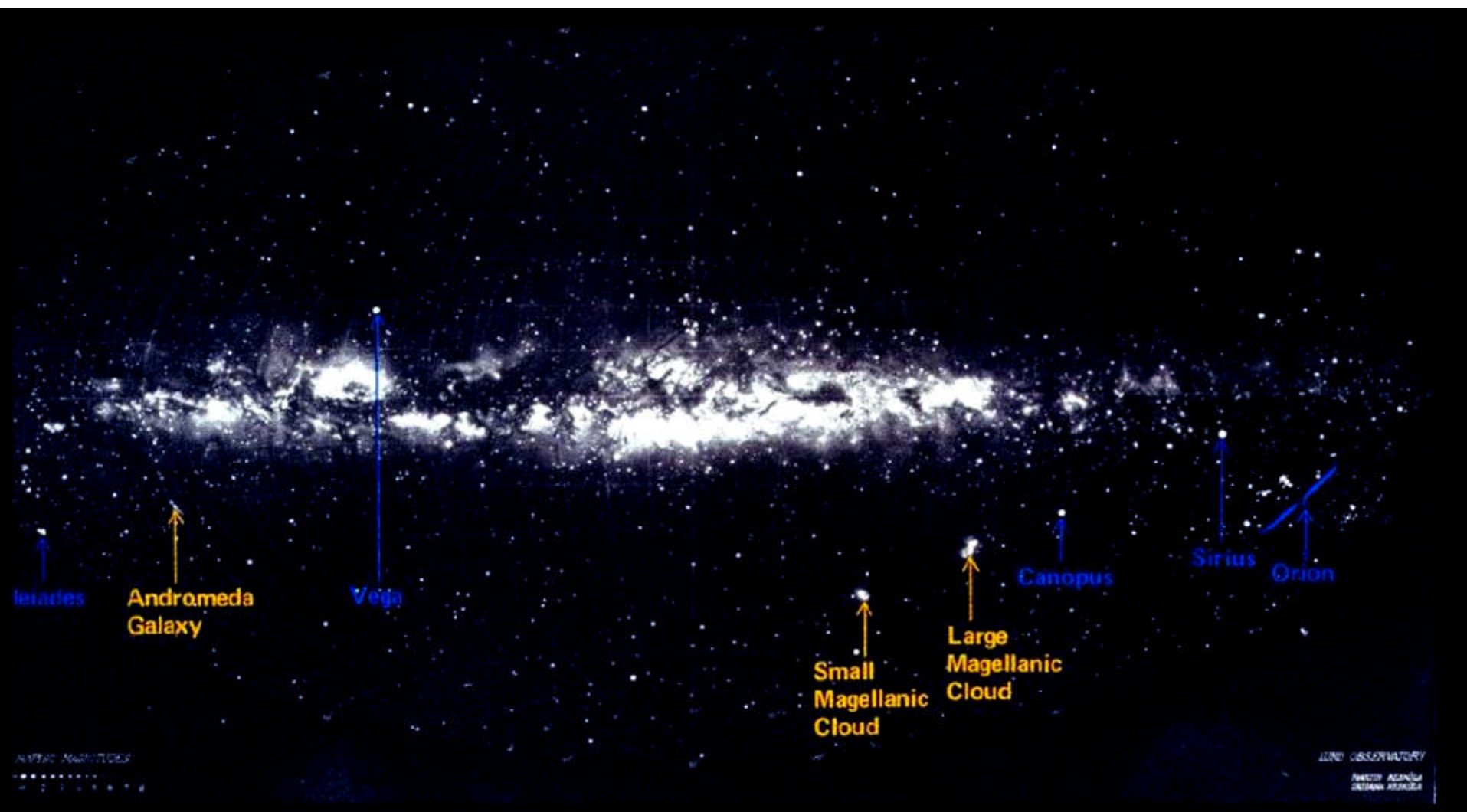


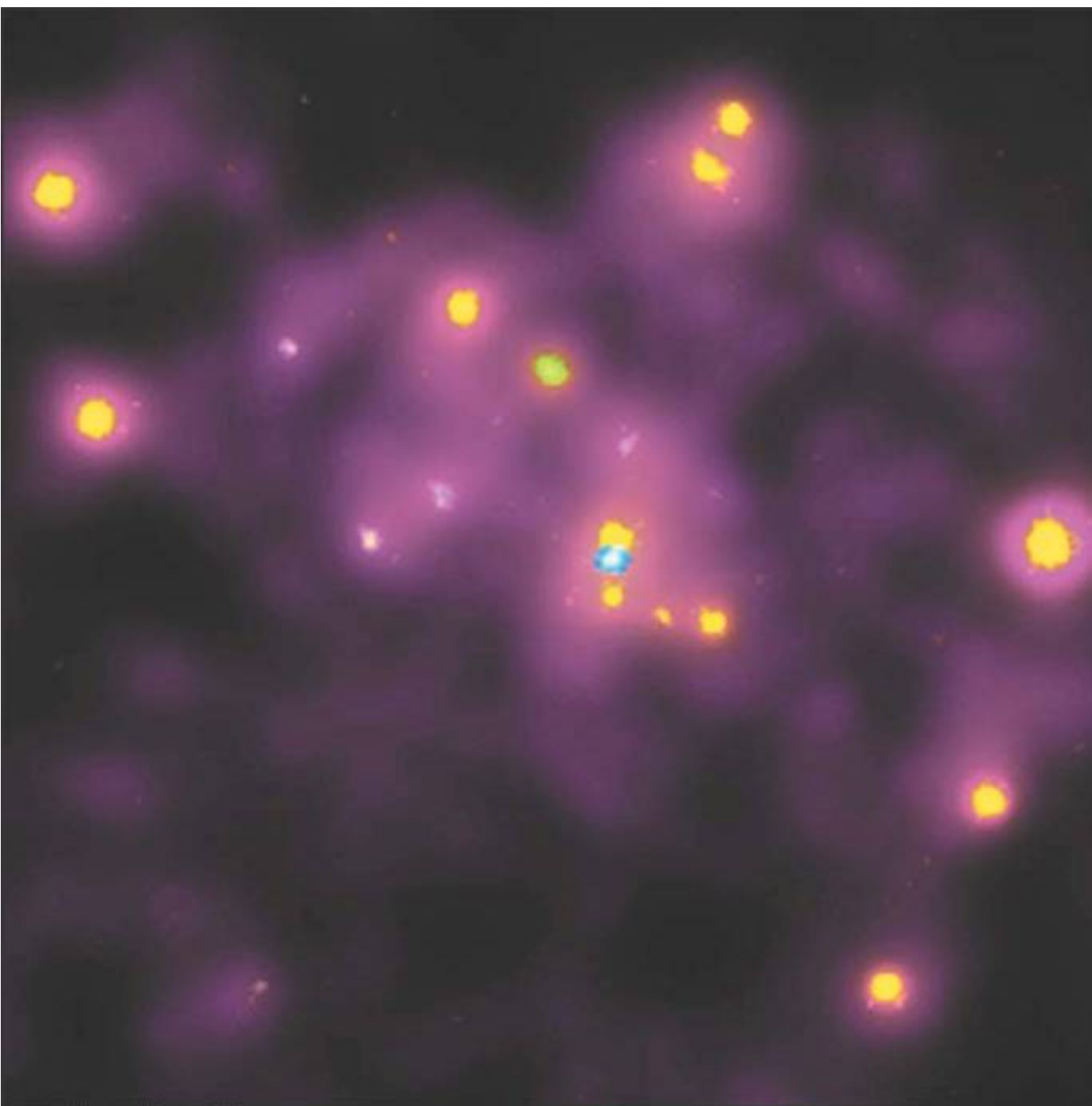


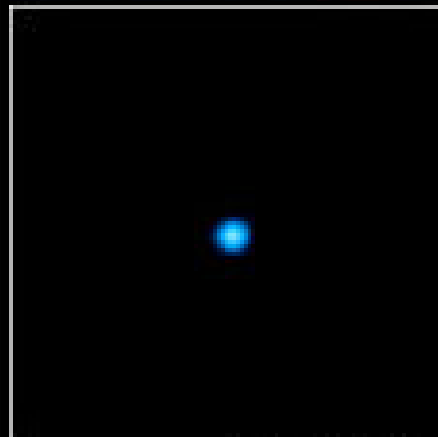


# Formation of extragalactic jets from black hole accretion disk

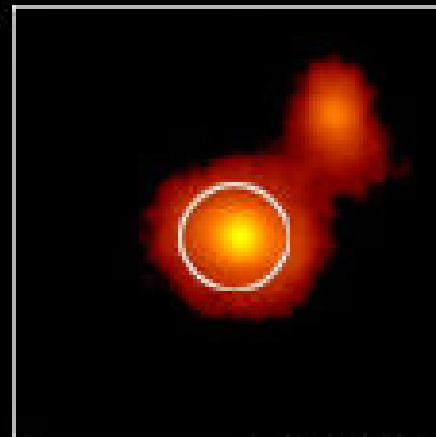








CHANDRA X-RAY



ESO OPTICAL

<http://www.astro.ucla.edu/~ghezgroup/gc/pictures/orbitsMovie.shtml>