Accretion processes in astrophysics

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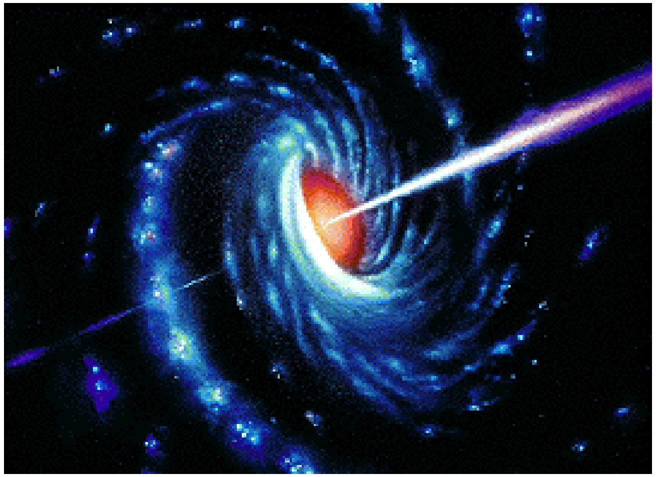
Lecture outline:

1. Accretion processes in astrophysics - an introduction
2. Basic parameters of accretion flow
3. Examples of accretion flow in astrophysical objects
4. Spherical accretion
5. Motion of a test particle in the gravitational field of a black hole
6. Classical accretion disks
7. Radiation transfer
8. Compton process and two-phase medium of accretion flow
9. Time evolution of accretion disks, stationarity, stability
10. Mathematical description of variability
11. Magneto-hydrodynamic simulations of accretion flows
12. Gamma-ray bursts, jet formation and unsolved problems
13. Applications: main sequence stars, white dwarfs
14. Applications: neutron stars and galactic black holes
15. Applications: active galactic nuclei

Cyg X-1 (upper panel) and active galactic nucleus (lower panel) – artist view



Literature:

Books:

1. “Accretion power in astrophysics”, Frank, King & Raine
2. “Radiative Processes in Astrophysics”, Rybicki & Lightman
3. “Black hole astrophysics: the engine paradigm”, David L. Meier
4. “Black-Hole Accretion Disks: Towards a New Paradigm”, Kato, Fukue & Mineshige

Original papers:

1. Shakura & Sunyaev, 1973, classical disk
2. Novikov & Thorne, 1973, GR version

My lecture will be much, much simpler, but you will find a lot of material there if you need more details.

Digression 1 ...

If you want to publish something important, it is better to be **fast**:

- Shakura & Sunyaev, 1973, sent to publication June 1972, and full GR lectures in Les Houches (Novikov & Thorne 1973) were done in the summer 1972

If you want to publish something important, it is better
(i) to be correct from the beginning,
(ii) to publish it in appropriate journal,
(iii) to put it into public archive, particularly when you did (ii) incorrectly

- Shakura & Sunyaev, 1973, **citations 9281**
- Lynden-Bell, 1969, **citations 1104**
- Shakura 1972, **citations 149**

Digression 2

Understanding of accretion requires (sometimes) the knowledge of GR, MHD, radiative transfer, atomic physics, chemistry and so on. Instead of doing a course on each of these topics prior to the analysis of specific objects, we will move slowly through the field, starting from simple issues, and later returning to them in some depth.

So I do not promise you to get a comprehensive knowledge of description of accretion but I plan to provide you with an understanding what we know and what you need eventually to make progress from the place where we are.

1. Accretion – definition

The word 'accretion' was not present in general encyclopedias, at least in Polish. No 'accretion' in large multi-part flag edition from 1962–1970 (Encyklopedia PWN). It appears in the New Encyclopedia PWN (1995), and it gives the definition (in Polish):

AKRECJA [łac.], spadanie rozproszonej materii na powierzchnię gwiazdy lub czarnej dziury. Podczas akrecji energia mechaniczna opadającj materii zamienia się w ciepło, czemu towarzyszy emisja promieniowania elektromagnetycznego; w skrajnym przypadku akrecji do czarnej dziury wypromieniowywana energia może wynosić 0.4 mc^2, gdzie m - ilość spadającej masy, c- prędkość światła w próżni. W większości przypadków, a zwłaszcza w układach podwójnych, materia podlegająca akrecji ma znaczny moment pędu uniemożliwiający bezpośrednie opadnięcie na powierzchnię gwiazdy; etapem pośrednim jest utworzenie się wokółgwiezdnego obracającego się dysku, tzw. dysku akrecyjnego; dopiero utrata momentu pędu przez część cząstek w wyniku oddziaływań z materią dysku powoduje ich dalsze opadanie.

My (Google) translation:

ACCRETION(latin), falling of dispersed matter on the surface of a star or a black hole. During accretion, the mechanical energy of falling matter turns into heat, which is accompanied by the emission of electromagnetic radiation; in the extreme case of accretion to a black hole, the radiated energy can be 0.4 mc^2, where m - the amount of falling mass, c- the speed of light in a vacuum. In most cases, and especially in binary systems, accreted matter has a significant angular momentum that prevents direct falling on the star's surface; the intermediate stage is the formation of a rotating disk around the star, known as accretion disk; it is only the loss of angular momentum by some particles as a result of interactions with the disk matter that causes them to further fall.

1. Accretion – definition

This definition was clearly inspired by ***technological progress*** in observational astronomy in the second part of XX century. Observations in the radio and X-ray band revealed new phenomena which needed new names.

In other vocabularies (e.g. The Macmillan Dictionary of Astronomy, V. Illingwort, 1979) there is no requirement of any action of the gravitational field. In that case accretion is understood as ***growth, fusion.*** We could then consider the formation of dust grains in the interstellar space or the formation of planetesimals in the early Solar System as accretion process.

In ADS the first paper containing ‘accretion’ in abstract or title is:

“Sul modo d'accrescimento dei cristalli e sulle cause delle variazioni delle loro forme secondarie”, Pasteur, L., 1856, *Nuovo Cimento*

But the most cited one is still the same:

1. “Black holes in binary systems. Observational appearance”, Shakura & Sunyaev 1973, citations 9281
2. “A Powerful Local Shear Instability in Weakly Magnetized Disks. I. Linear Analysis”, Balbus & Hawley, 1991, citations 3061

1. Accretion – definition

Accretion can be thus understood very generally, or in a more narrow way. In my lecture I will concentrate on accretion caused by the gravitational interaction.
Still, some examples of a falling down in gravitational field are not spectacular:

- rain (it is really accretion ? Or rather circulation ?...)
- meteorites (e.g. Tunguska event in 1908, Chelyabinsk event in 2013, or Chicxulub impact which might have caused the massive Cretaceous–Paleogene extinction some 66 milions of years ago)
- Impact of Shoemaker-Levi 9 comet on the Jupiter in 1994
- Fate of many sungrazing comets

Those examples are not spectacular if the energy rate liberated in the event is compared to the solar luminosity.

In my lecture I will concentrate on objects which look and behaviour is predominantly determined by the process of accretion.

In case of stars this happens in close binary systems which exchange mass. The process is frequently drammatic, accompanied by strong outbursts. Accretion onto black holes offers an explanation of the galactic nuclear activity. Gamma-ray bursts also can be considered as examples of accretion, and finally merging stars (neutron stars or black holes) sending the gravitational wave signal to LIGO/VIRGO instruments are also accretion.

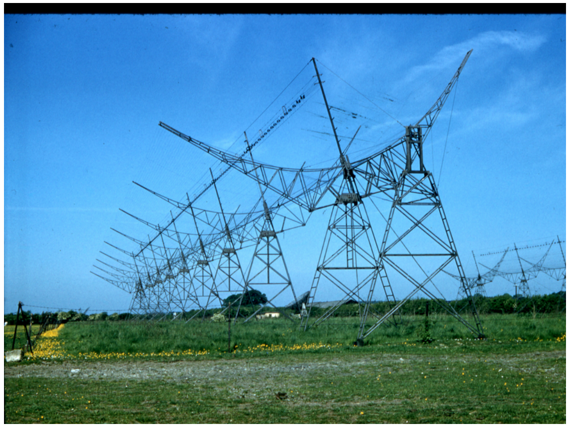
Thus all most luminous sources in astronomy are accretors.

Astronomers established that as a result of instrumental development: radio and X-ray observational windows.

Discovery of quasars

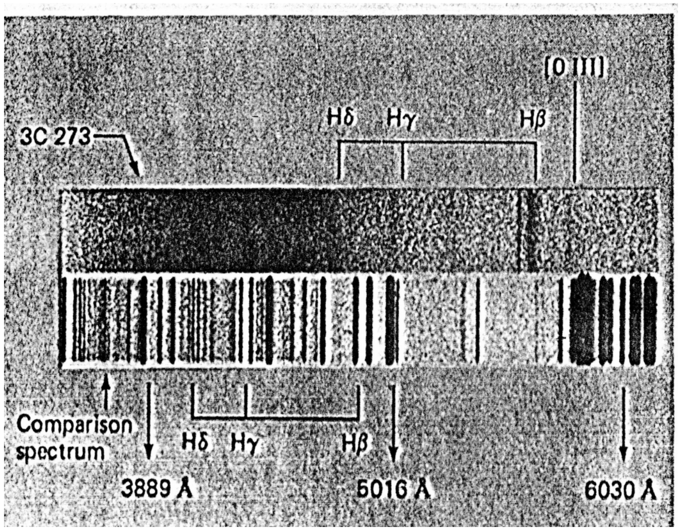
Radioastronomy was born after II world War making use of military technology. It was discovered soon that some galaxies emit radio. Active people of that time: Shklovskii, Vorontsov-Velyaminov, Vorontsov-Velyaminov (since 1955), paying attention to galaxies with broad emission lines. In Cambridge, a number of systematic surveys of the radio sky were performed, but first catalogs referred to stars.
Some of those point-like sources (e.g. 3C 273, 3C 48) looked like stars, but the optical spectrum of 3C 48 did not look like a star, and 3C 273 had no optical counter part. Then in 1963:
- optical counterpart for 3C 273 was found using the lunar occultation (Hazard)
- optical spectrum was obtained (Oke & Schmidt)
- emission lines were identified as Balmer lines, but redshifted, with z = 0.158 (Schmidt).

Antenna used for 1C catalog (from R. Wielebiński)



Antenna used for 3C catalog (from R. Wielebiński)

Determination of the distance for a known magnitude 12.6 implied liberation of huge energy in a very compact region, and in addition image showed the presence of the jet. Interpretation: accreting black hole (Zeldovich 1964, Salpeter 1964)



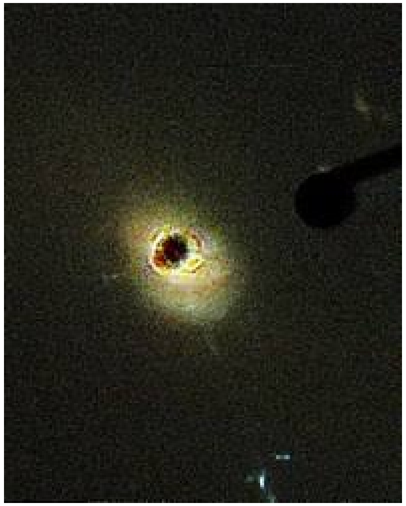
The optical spectrum of 3C 273 from Schmidt (1963)

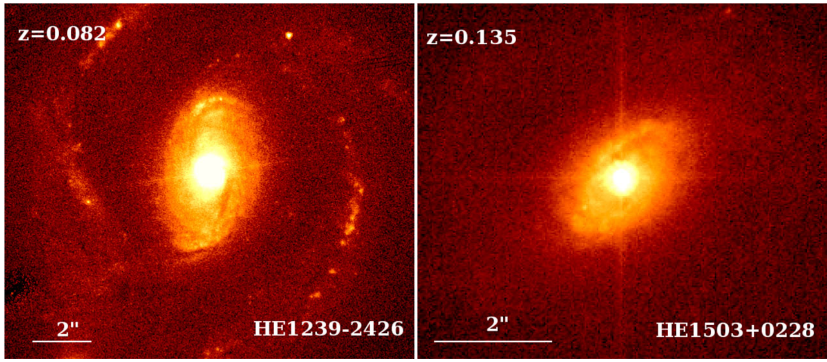
Quasar – quasi stellar object

Digression – quasars vs. current view

Quasars were first defined as unresolved in the optical image point-like sources (apart from the jet), with host galaxy invisible. Now quasars belong to the general group of active galaxies, and host galaxies of quasars of not too distant quasars are routinely studied.

3C 273 as imaged by the Hubble Space Telescope's Advanced Camera for Surveys. Light from the bright quasar nucleus is blocked by a coronagraph so that the surrounding host galaxy can be more easily seen. Credit: NASA/ESA (wikipedia).





Two fainter quasars where the host is easily visible in HST without coronagraph (Credit: HST/ESO)

Quasar 3C 273 taken by Hubble Space Telescope, without coronograph (wikipedia)

Currently the term 'quasars' is still used for brighter AGN. There is no formal definition, although there were attempts to consider as quasars sources which are brighter than 44.5 in log (nuLnu) in the V band rest frame.

It is more difficult to determine the division between active and non-active galaxies. All contain supermassive black holes, and all accrete, as we know now. But not all contain broad quasar-like emission lines. So frequently we refer to those, which contain such lines, as active.

Digression – quasars vs. current view cont.

What is log nuLnu?

AGN spectra are usually plotted in two ways, depending on the aim of the plot: linear plot Flux vs. Lambda or logarithmic plot log nuFnu (or log nuLnu) vs. long nu

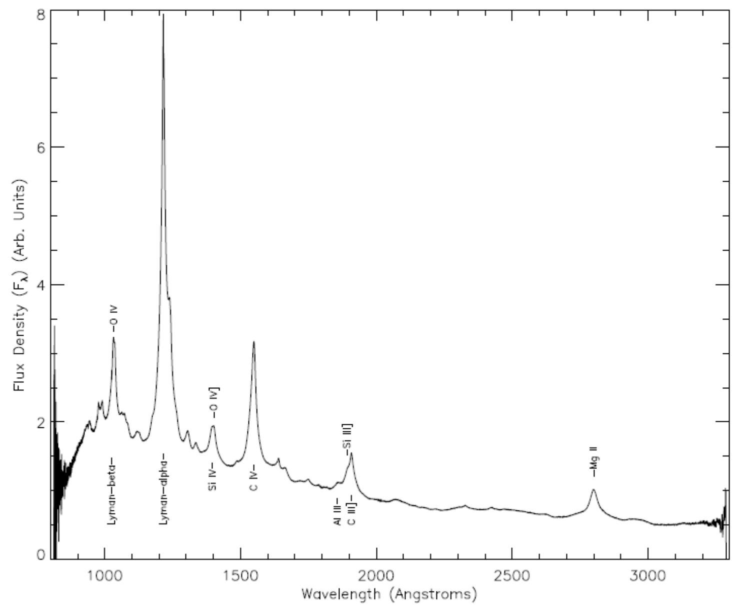
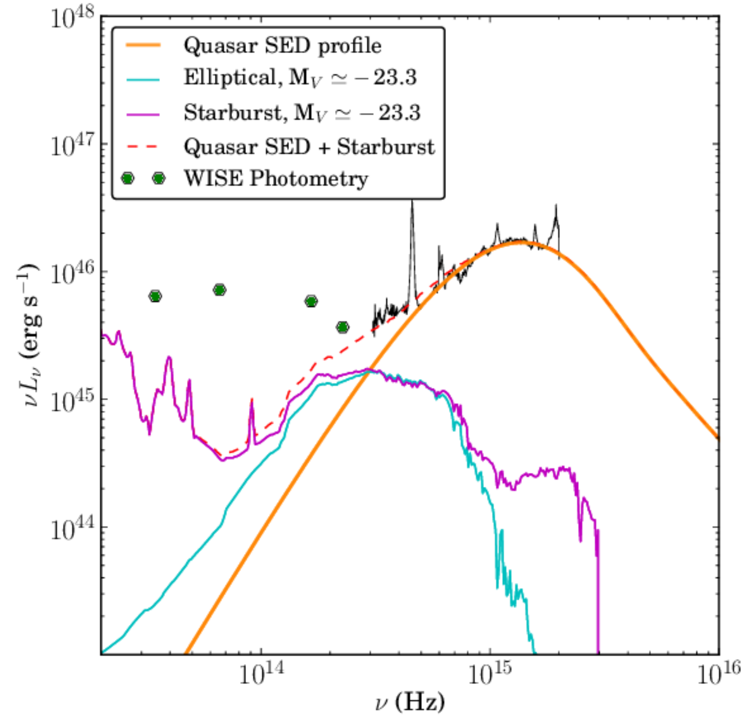


Figure 8. Optical depth corrected quasar composite spectrum after having been warped to match the median spectral index of the quasar sample as described in Section 4.1. This composite spectrum represents the final product of this work and is available for download at a publicly accessible website[a].

[a]http://data.sdss3.org/sas/dr12/boss/qso/composite/

Quasar composite spectrum from SDSS/BOSS, Harris et al. (2016), only UV rest frame part is visible since those were intermediate/high redshift quasars.

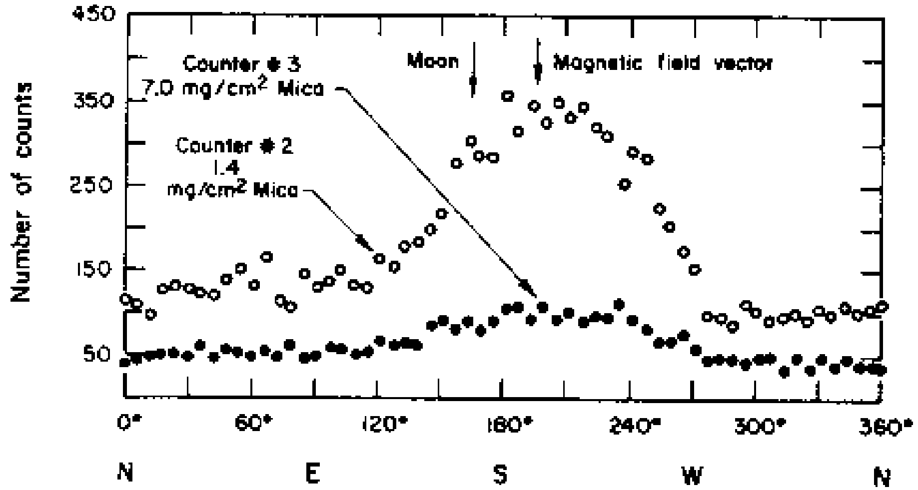


Quasar spectrum (object J2328+1500) from Collinson et al. (2015).

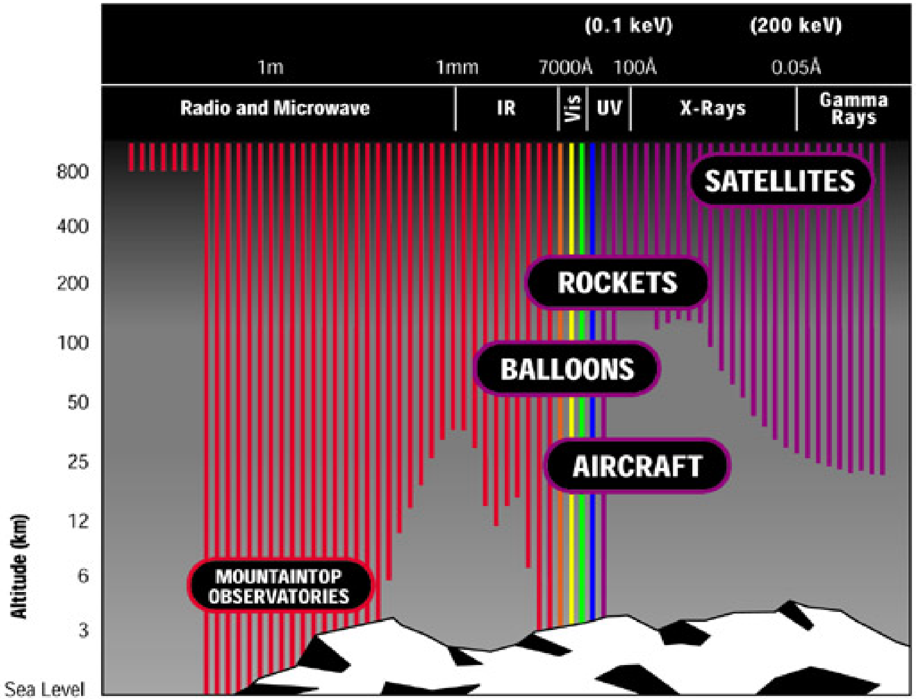
Left figure shows better the line profiles, while the right figure shows better the shape of the continuum, including the immediate information where most energy is emitted (peak on the diagram).

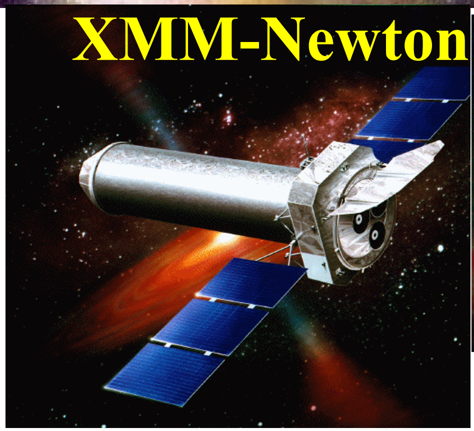
Wikipedia

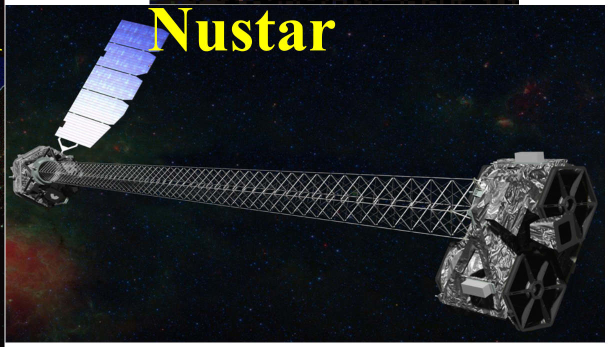
Discovery of galactic X-ray binaries



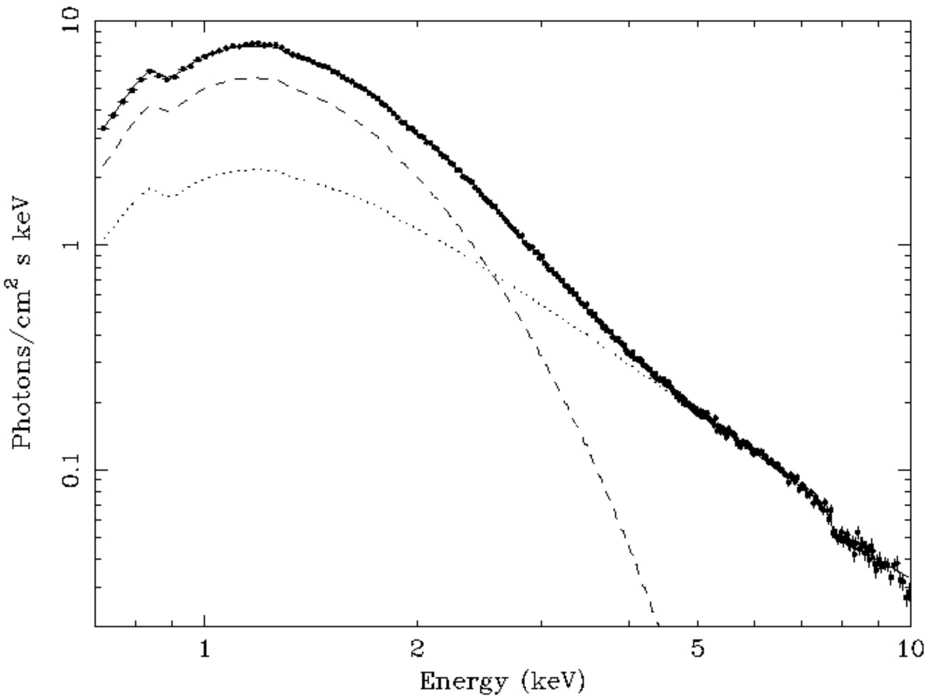
Riccardo Giacconi, his observation of Sco X-2 and the rocket he used (Aerobee).







Digression – why X-rays?



X-ray spectrum of an X-ray binary in a soft state measured by ASCA satellite from Dotani et al. (1997); most energy is emitted in the X-ray band. In addition, sources are heavily absorbed in UV and soft X-rays by the interstellar medium.

In this source, in the optical band, we see the companion star (bright massive star – O9.7Iab), and not the accretion flow onto the compact object (black hole in this case).

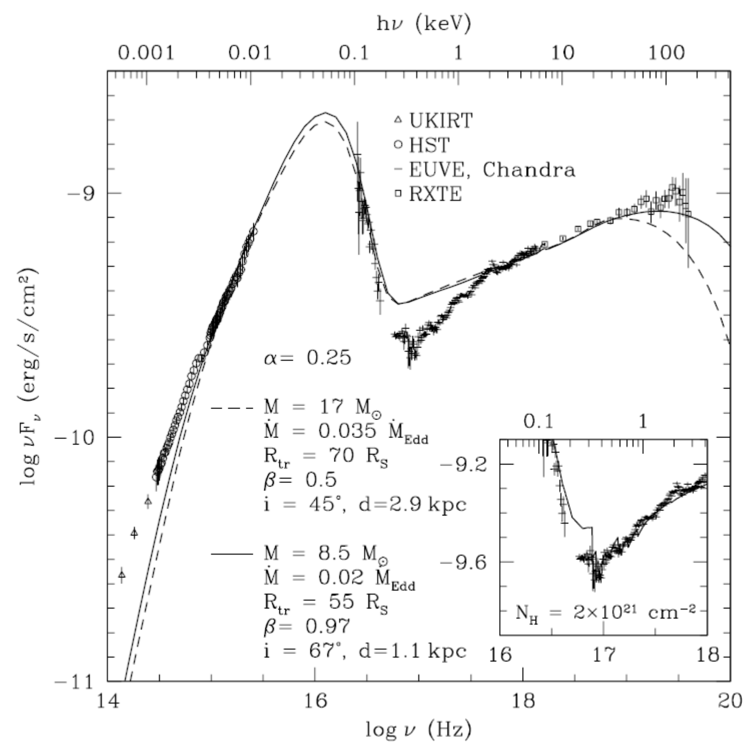


FIG. 1.—Model spectra for different parameter values are shown together with the data from PI, corrected for interstellar absorption with $N_H = 1.15 \times 10^{20}$ cm^{-2} (see § 4). The model in the inset incorporates the effects of a warm absorber (see text for details). [*See the electronic edition of Journal for a color version of this figure.*]

X-RAY NOVA XTE J1118+480

In hard state most of the emission comes out in UV, but in galactic sources this is usually unobservable anyway due to extinction. One example is this source *(Esin et al. 2001).*

3. Some numbers

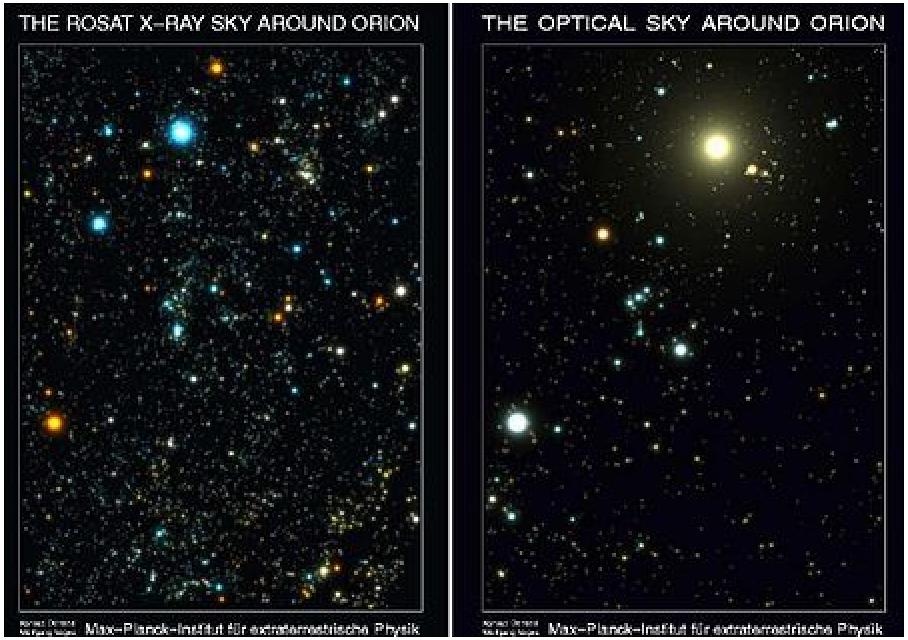
The strong accretion phenomenon may see rather unfrequent: we observe that only 1 star per milion in our Galaxy currently exchanges mass with its companion. However, statistically, 1 per 100 stars passes through some mass echange period in the course of its evolution. In addition, visual impression which we have from the sky depend on the wavelength we use. If we look at the sky in the optical band by eye or a small telescope, we see non-accreting stars. In X-rays, apart from the Sun (the brightest X-ray source on the sky) we mostly see accreting objects.

In ROSAT catalog (X-ray satellite, All Sky Survey)

- **stars 3-5 %**
- **AGN (active galactic nuclei) 95%**

Activity of galaxies:

- weak but visible (LINER) – ok. 30 %
- Seyfert galaxies - a few %
- bright Seyfert galaxies - 10^{-3}
- bright radiogalaxies - 10^{-5}
- quasars – 10^{-6}

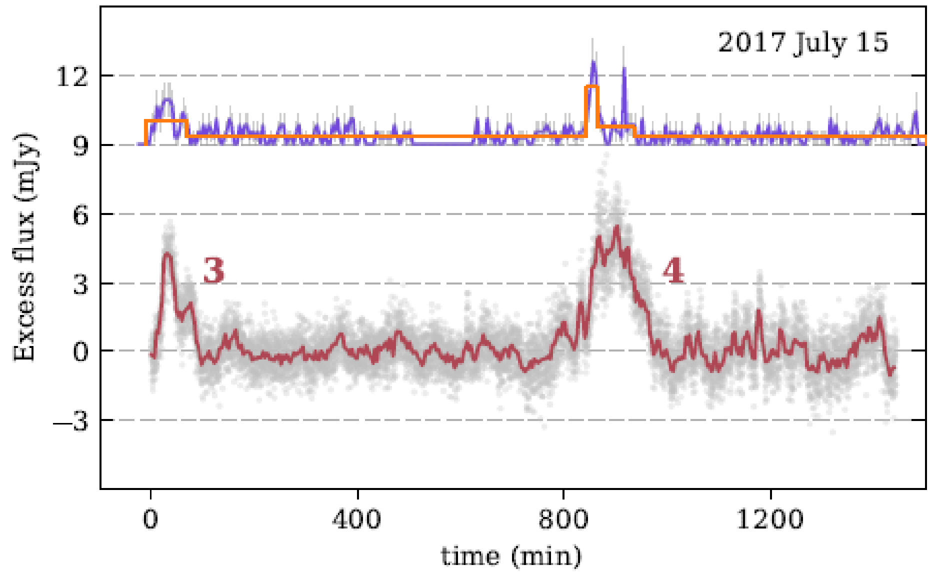


Orion region: optical image (left) and ROSAT image (right), wikipedia

However, again in a statistical sense, all galaxies were passing through at least a bright Seyfert stage, probably multiple times. These periods of activity affected also the galaxy formation, and in particular the star formation rate. Jest jednak niemal pewne, że wszystkie galaktyki na wczesnym etapie rozwoju przechodziły przez fazę "bycia kwazarem" czy choćby "bycia galaktyką Seyferta" i aktywność odgrywała rolę w procesie formowania się galaktyki jko całości. Obserwacje z HST wskazują na obecność czarnych dziur w stosunkowo słabo aktywnych galaktykach jak M87, istnieje też zaskakująco uniwersalny związek pomiędzy masą czarnej dziury a masą zgrubienia centralnego galaktyki macierzystej, niemal niezależny od poziomu aktywności galaktyki. W naszej galaktyce (Mleczna

Digression 1 – Sgr A*

Milky Way is currently a very weakly active, we see this activity only due to proximity to the nucleus. Milky Way hosts a black hole of the mass $4.02\times10^6\,M_s$ (Boehle et al. 2016).



Central regions shows flares in X-ray and in the near-IR band, optically the region cannot be observed due to extreme extinction.

One example of Chandra X-ray lightcurve (upper panel) and Spitzer IR lightcurve (lower panel) from Boyce et al. (2019).

Signatures of past activity: light echo in molecular clouds from an outburst of some 400 years ago *(left; here from Ponti 2010),* and remnants of strong outburst some 10 milions of years ago - Fermi Bubbles (right)

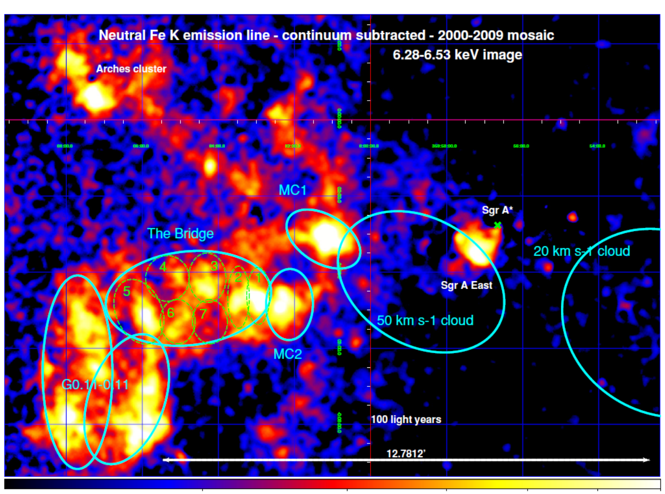
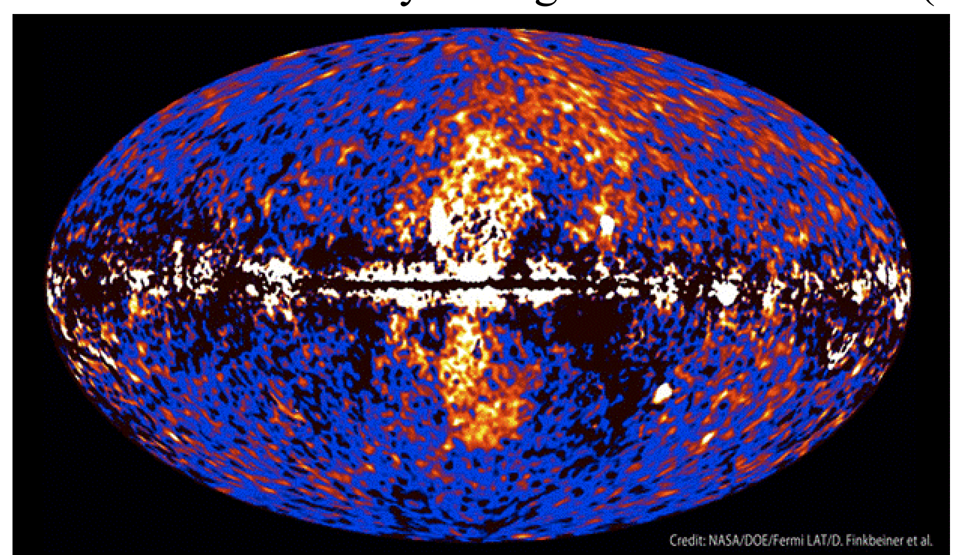


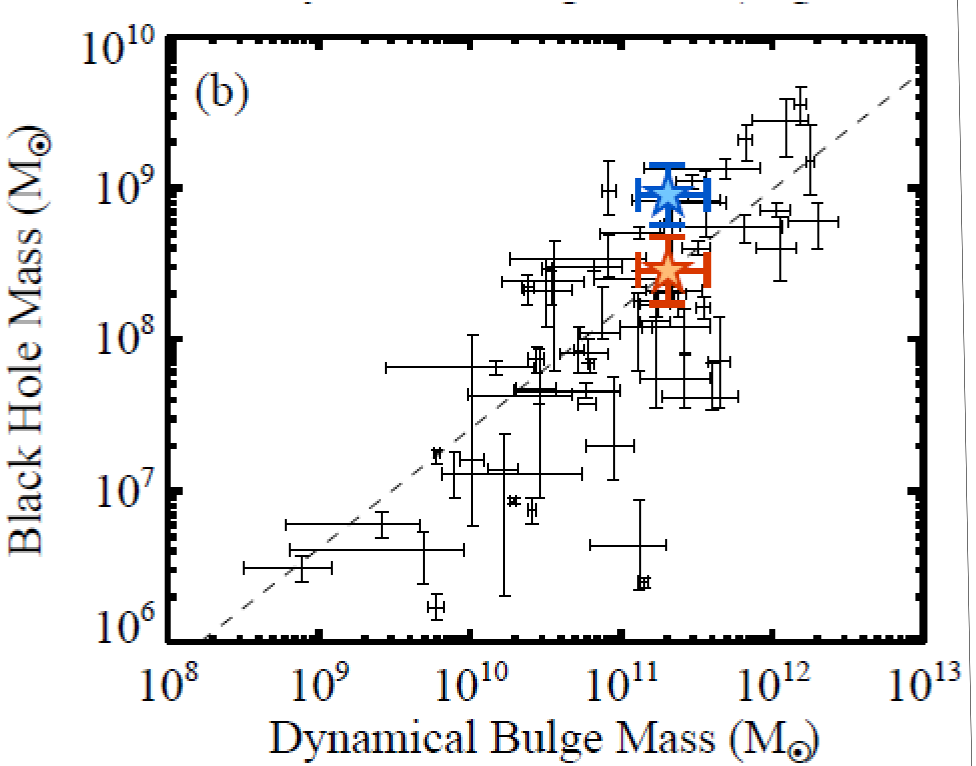
Figure 2. Enlargement of the Fe K, continuum-subtracted intensity map. The solid light blue ellipses show the regions selected through the study of the CS maps and the comparison with the Fe K map. These should indicate and separate the emission from the different MCs. The corresponding background regions have been selected



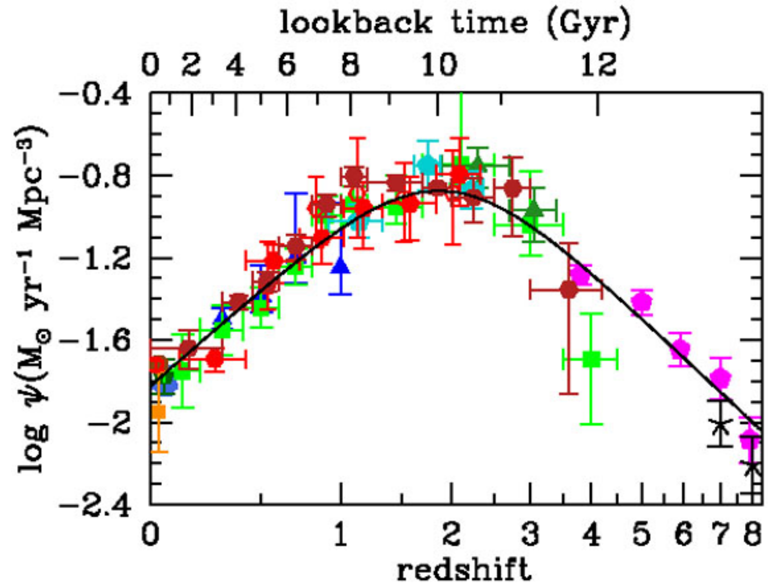
Digression 2: why we think that AGN activity is important

In 1998 Magorrian et al. discovered the linear dependence between the mass of the central black hole and the bulge mass of the host galaxy.
In 2004 Hearing et al. gave the value

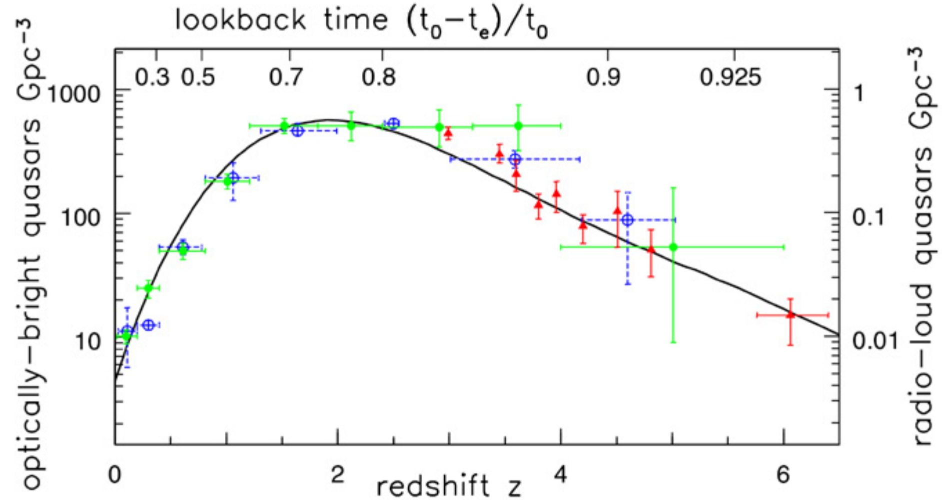
M_BH = (0.14% +/- 0.04%)M_bulge



From Inskip et al. (2011).



Star formation rate as a function of redshift (Madau 2014).



Number density of bright quasars as a function of redshift (Sparke & Gallagher 2007).

4. Importance of accretion - summary

I did not mentioned that so far, but accretion is a key phenomenon in formation of young stars and planetary systems surrounding them. So we cannot understand the formation of Earth, and appearance of life, without accretion.

So summarizing the role of accretion:

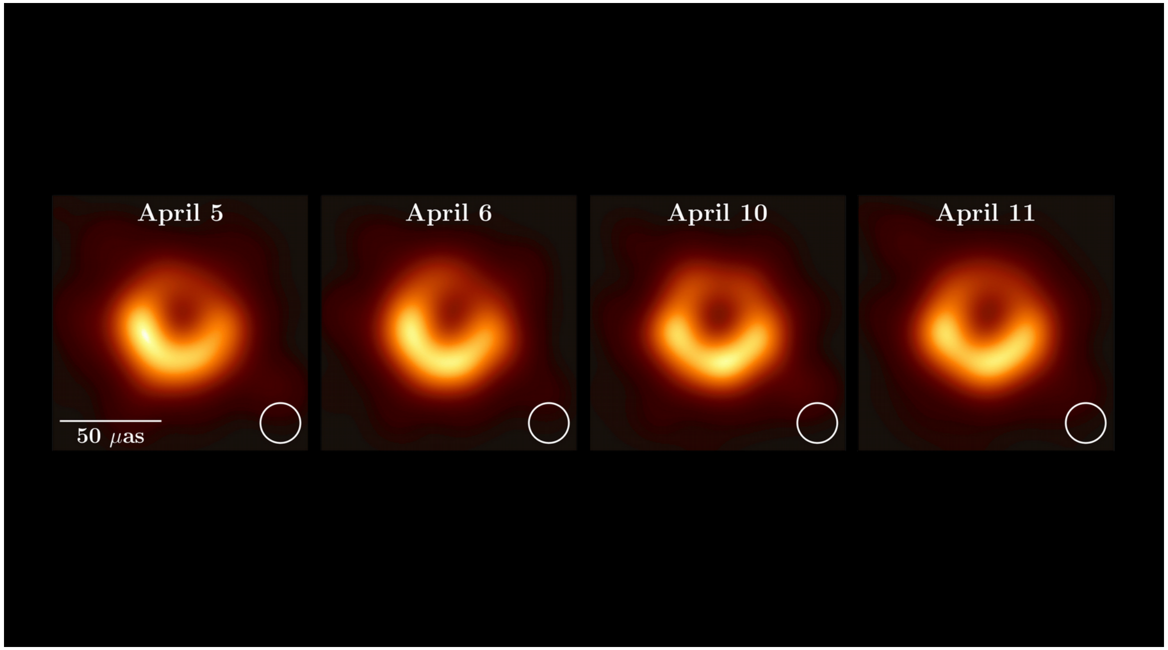
- **because of extension of the observational windows we use to understand the universe (whole electromagnetic spectrum, plus neutrinos, plus gravitational waves) the modern astronomy is significantly dominated by the issues related to accretion**
- **without understanding accretion, we cannot describe the formation of planetary systems**
- **without accretion, we cannot understand the evolution of significant fraction of binary stars**
- **Without accretion, we cannot understand the evolution of galaxies**

Understanding the accretion process, in turn, require the knowledge of several branches of physics, and we still have a lot of problems with that. The progress is quite slow. But we have an increasing stream of high quality observational data which motivates to work harder on the theory and give hints as for the most promising directions.

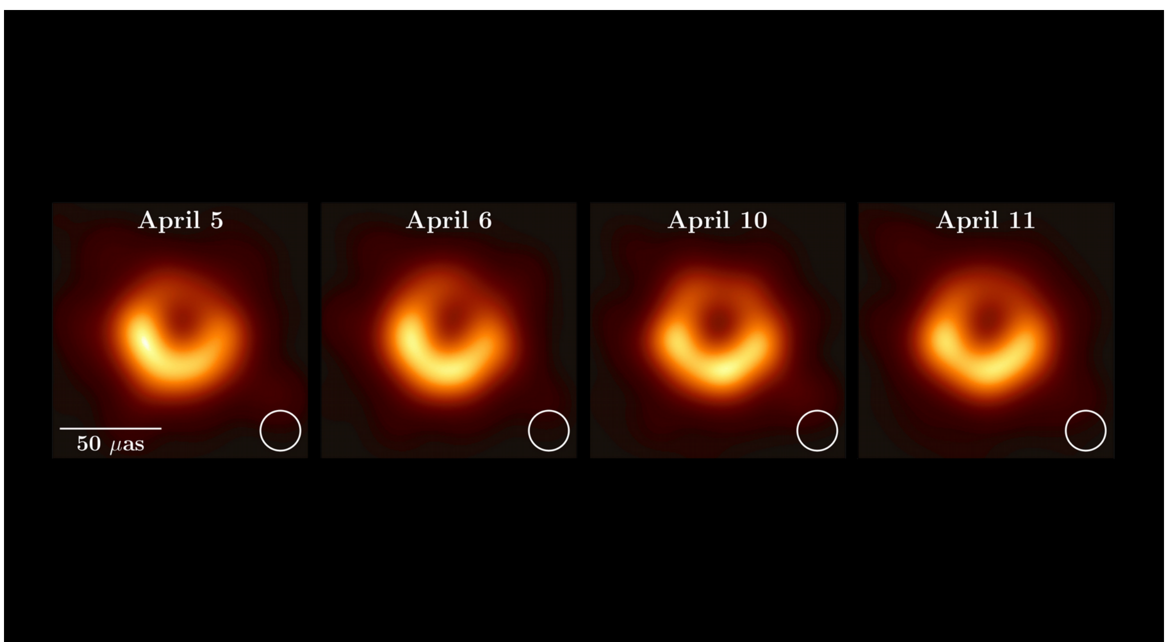
So the lecture will be an attempt to show where we are now, and at the same time it will provide an overview of several branches of physics.

More practically, the aim of the lecture is to discuss the types of sources which properties are dominated by accretion and to show you which part of physics we should use to gain the understanding of the on-going processes.

Digression: why we need a theory?



M87: Hot optically thin accretion disk (Event Horizon Telescope Collaboration et al. 2019)



M87: Jet (Davelaar et al. 2019; same model but with non-thermal electrons)

5. Sources of energy

Observation require emission, and emission of radiation requires energy. In the case of strong radiation sources, the first question is about the source of energy.

There are various energy sources, and they differ considerably in the efficiency and availability. The efficiency can be characterized by the information, how much energy we can get from the unit of a fuel. It is most convenient to use dimensionless definition of the efficiency, based on Einstein principle of mass and energy equivalence ($E = mc^2$):

$$\eta = \frac{\Delta E}{mc^2}$$

where ΔE is the energy liberated in the process, and m is the rest mass of the used fuel.
We can identify the basic types of the processes which lead to energy liberation: chemical, nuclear and gravitational. Their efficiency is easy to estimate, although the exact values depend on the specific setup.

Chemical processes

Chemical processes lead (sometimes) to energy liberation. Examples: burning (rapid reaction with oxygen). Reactions are based on Coulomb interaction of electron shells. We can roughly estimate it using the information about the binding energy of an electron in a hydrogen atom.

The phenomenon is quantum in nature, and this is why Planck constant appears in the formula for the binding energy state of the electron in hydrogen atom (ground state).

$$E_i = -\frac{m_e e^4}{2\hbar^2}$$

But this equation can be easily derived using the Bohr model of atom and informal approach:

$$E = \frac{1}{2} m_e v^2 - \frac{e^2}{r}$$

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Zjawisko jest z natury rzeczy kwantowe, o czym przypomina obecność stałej Plancka we wzorze na energię poziomu podstawowego atomu wodoru

Quantum mechanics

$$E_i = -\frac{m_e e^4}{2\hbar^2}$$ And this equation can be easily derived as: $$\frac{e^2}{r^2} = \frac{m_e v^2}{r}$$ $$m_e v r = n\hbar$$ $$n = 1$$

5. Sources of energy.

Ionization of hydrogen atom - 13.6 eV (1 Rydberg)
Rest mass of a proton - 511 keV×1836 = 0.94GeV Efficiency - 1.4×10^{-8}
The efficiency of real chemical sources of energy is determined in a laboratory.

source	*heat of combustion*	*efficiency*	
natural gas	5400 kcal/kg	2.5×10^{-10}	
coal	8730 kcal/kg	4.1×10^{-10}	
oil	11520 kcal/kg	5.3×10^{-10}	
hydrogen	33990 kcal/kg	1.6×10^{-9}	(less than a rough estimate above)

DIGRESSION: units of energy, heat etc.

in SI : 1 J ; w cgs: 1 erg = 10^{-7} J; 1 keV = 1.602177×10^{-9} erg; 1 cal = 4.184 J
Zombeck, "Handbook of Astrophysics", Internet Edition (available now after registration)

Nuclear reactions:

Burning hydrogen lead to creation of helium (e.g. in the Sun and other main sequence stars).
Schematically $4p \rightarrow {}^4He$
Efficiency is determined by strong instead of electromagnetic interation, and as for the order of magnitude (or worse) it is comparable to the electron rest mass (1 MeV). More precisely:

process	*energy gain/nukleon*	*efficiency*
burning hydrogen to heliu	7.1 MeV	0.0075
Burning helium to iron	1.5 MeV	0.0016

Iron (Fe) has the highest binding energy per nucleon, burning usually stops there, this is why Fe is so abundant.

5. Sources of energy

Burning hydrogen is the mechanism behind the radiation of the Sun (and other main sequence stars), and takes place in its interior. The reactio is not as simple as implied on the previous page. The basis process in low mass stars is called proton-proton fusion (or pp cycle) and it happened in three stages:

$^{1}H + ^{1}H \longrightarrow ^{2}D + e^{+} + \nu_{e}$ $\quad 7.9 \times 10^{9}$ years

$^{2}D + ^{1}H \longrightarrow ^{3}He + \gamma$ $\quad 1.3$ s

$^{3}He + ^{3}He \longrightarrow ^{4}He + 2\,^{1}H$ $\quad 2.4 \times 10^{5}$ years

In massive stars CNO cycle is more efficient, and in this process elements C, N and O acts as catalysts. At the end of its life, stars can use helium and more heavy elements as fuel, but this stage is not so long lasting.

Gravitational sources of energy

Potential energy of a small mass m, available to be changed into heat if the body falls dawn from infinity onto another body of a mass M and the radius R is $\frac{GMm}{R}$

The process efficiency $\quad \eta = \frac{GMm}{Rmc^2} = \frac{GM}{Rc^2}$

It is convenient to introduce a quantity which allows to see the value of this ratio immediately, and this quantity, which characterizes the body M is

$R_{Schw} = \frac{2GM}{c^2}$ In cgs: $R_{Schw} = 2.95 \times 10^{5} \times \frac{M}{M_s}$ $[cm]$ we then get: $\eta = 0.5 \frac{R_{Schw}}{R}$

This convenient quantity is known as **Schwarzschild radius.**

This is the radius of the horizon of the non-rotating black in in General Relativity. **Thus efficiency of accretion process is high when the infalling small body m hits the surface of the body M, and the radius of the large body M is close to its Schwarzschild radius.** For Sun R_{Schw} = 3 km.

5. Sources of energy

Some examples in numbers:

object	*mass*	*radius*	*R/RSchw*	*efficiency*
Moon	$0.0123\ M_Z$	$0.2725\ R_Z$	1.6×10^{10}	3.1×10^{-11}
Earth	5.976×10^{24} kg	6378 km	7.2×10^{8}	7.0×10^{-10}
Jupiter	$317.893\ M_Z$	$11.27\ R_Z$	2.6×10^{7}	2.0×10^{-8}
Sun	1.989×10^{30} kg	696 000 km	2.4×10^{5}	2.1×10^{-6}
Sirius B*	$1\ M_s$	$1/30\ R_s$	7.9×10^{3}	6.5×10^{-5}
Cen X-1 &	$0.6 - 1.8\ M_s$	~10 km	~3	0.15
Cyg X-1#	$10\ M_s$		1	0.5 (?)
3C 273 #	$5\times10^{8}\ M_s$		1	0.5 (?)

* *white dwarf*

& *neutron star; its optical counterpart is known as Krzemiński star*

\# *black holes; since they do not have the surface, the formula actually should not be applied, we will talk about it later in great detail.*

Accretion can easily be extremely efficient !