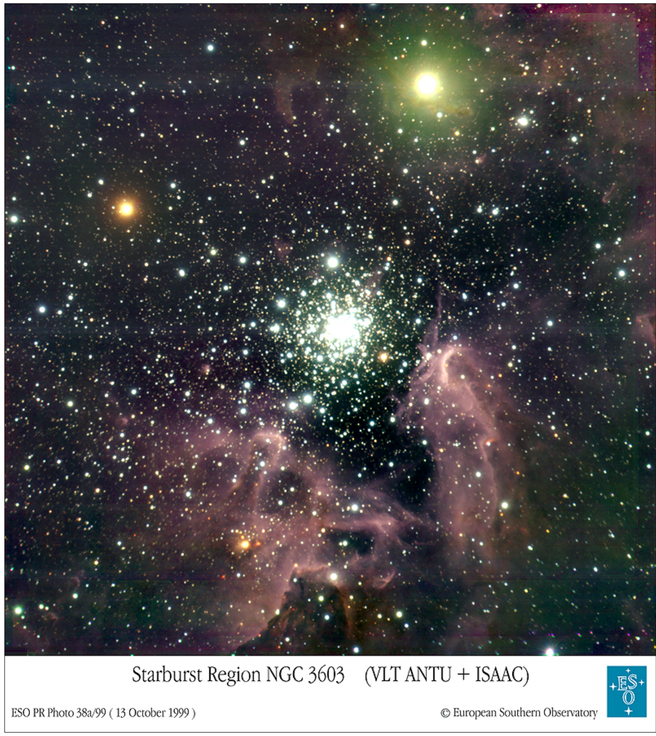
Accretion processes in astronomy



1. Protostars

Formation of a new star in a process of the collapse of protostellar cloud is complex, with an important role of gravity, pressure, rotation, magnetic field and opacity. The photo (right) from VLT instrument shows a star forming region in **NGC 3603.** Formation of massive stars ($M >$ a few M_s) proceeds in a different way than formation of much less massive stars. For massive stars, the process is violent, significant fraction of the protostellar cloud forms a star, probably an accretion disk temporarily forms and helps to transport the angular momentum but we do not observe this phase. We only see the star when it is formed. Formation of less massive stars, well observed e.g. in Taurus Molecular Cloud or in Orion nebula is understood much better. Star forms more slowly through a stage of disk accretion (e.g. HL Tau, DG Tau, GW Ori). In a large fraction of systems a binary star forms. Numerical simulations helped to understood the process.

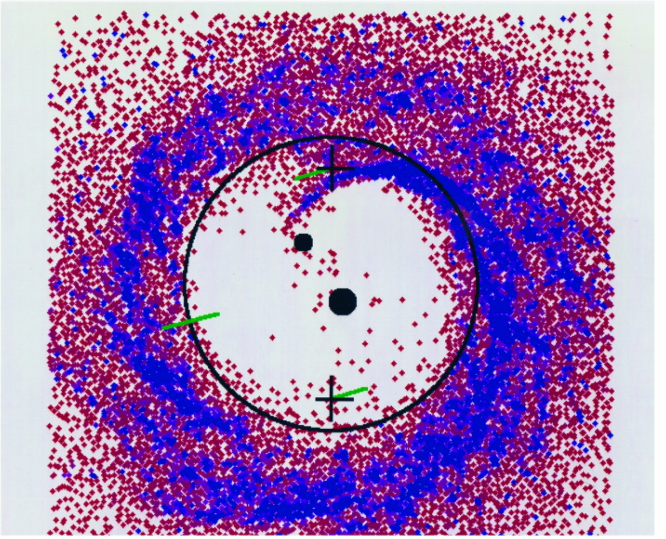


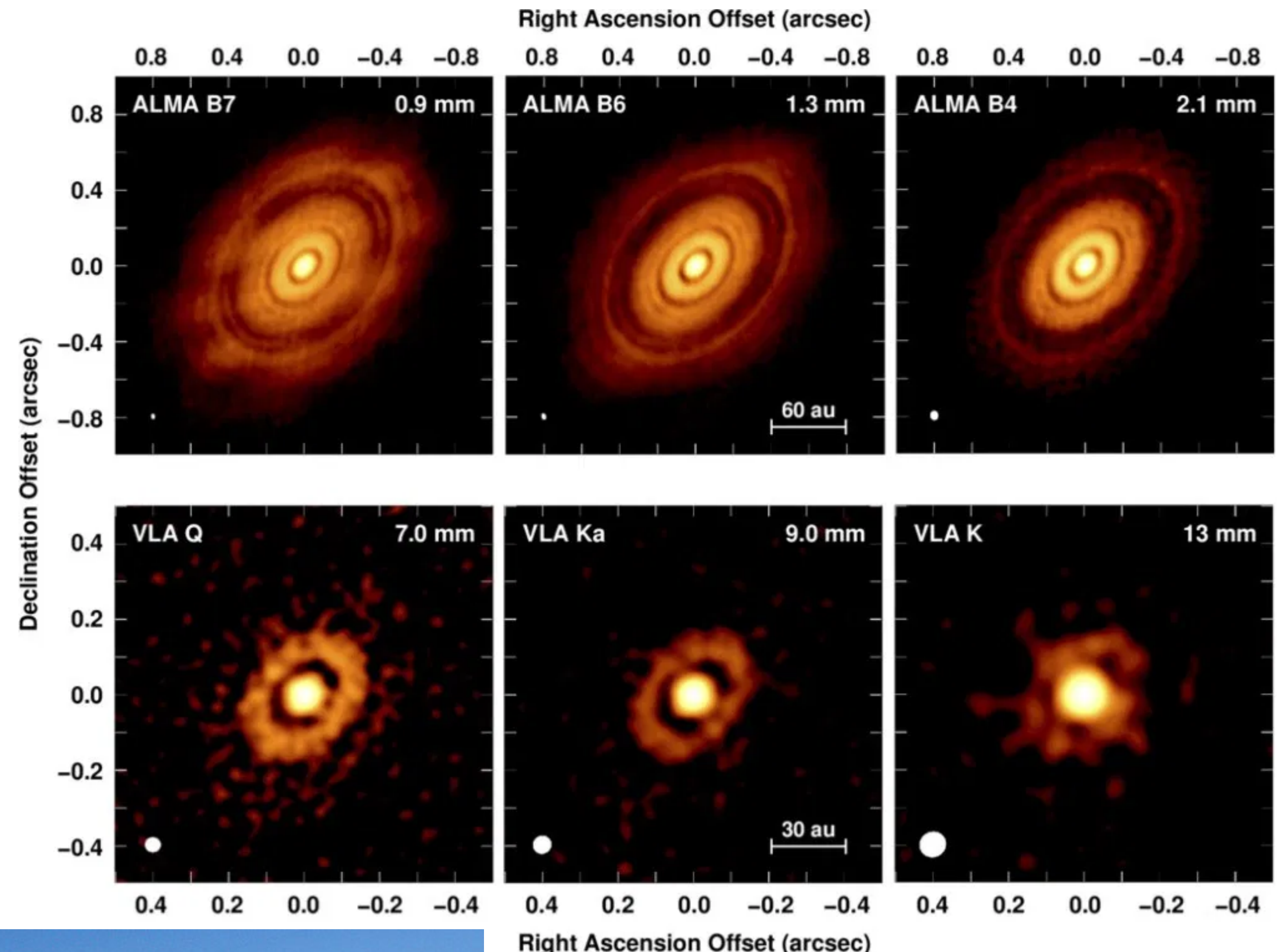
FIG. 1c

The binary star is inside the accretion disk, the black circle marks the position of the Lindblad resonance. Computations were used using SPH code.
Lubow & Artymowicz (1996), 467:L77.

Accretion processes in astronomy

1. Protostars

Nowadays we can map this process directly with the modern instruments like ALMA.



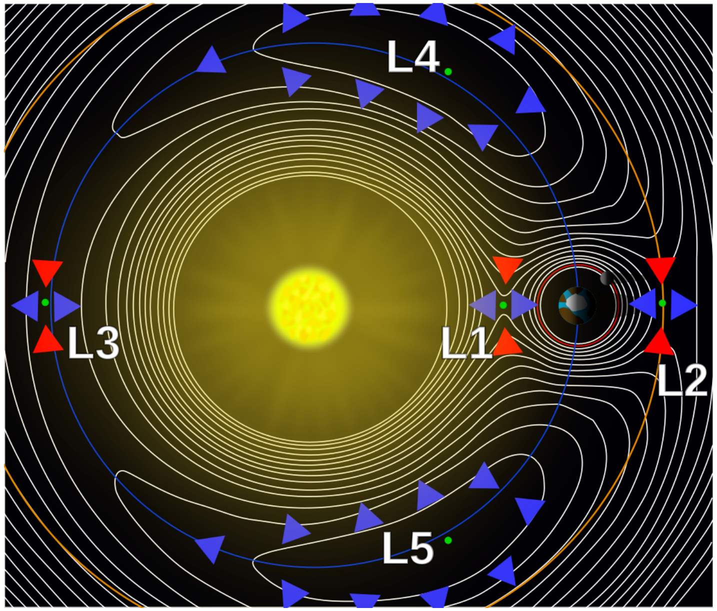
The Dust Particle Radial Distribution in the HL Tau Disk from ALMA and VLA (Carrasco-Gonzalez et al. 2019)

Atacama Large Milimeter Array (ALMA)

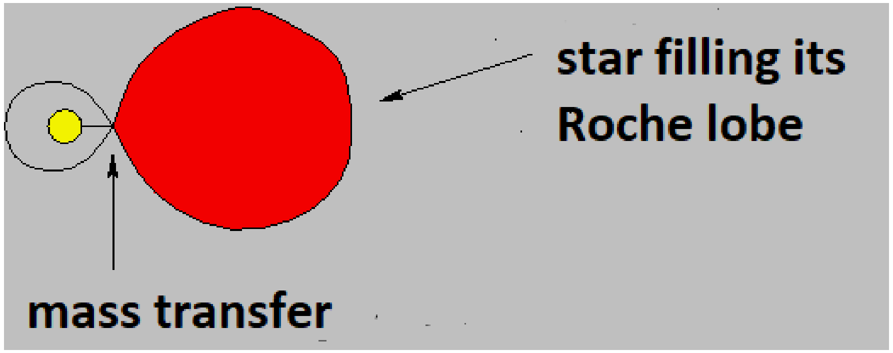
2. Binary stars

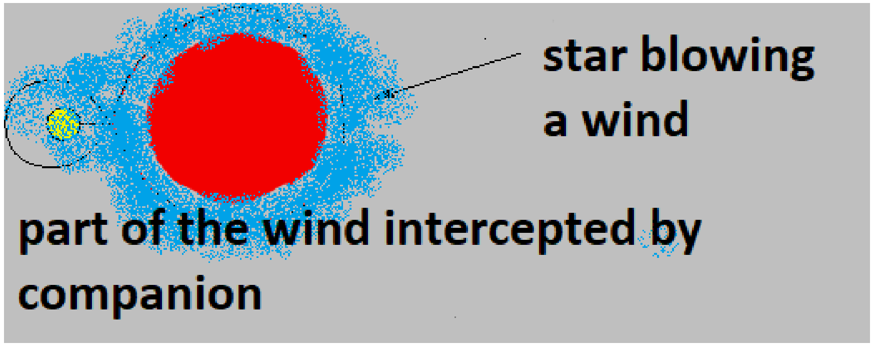
Considerable fraction of the stars (about half) forms as binary systems, with the period of a few to dozens of years. Statistical studies of the stars similar to the Sun, in our part of the Galaxy, indicate that about ~ 70 % of stars are in binary systems, the mean period is 180 lat, and half of them has periods from 100 days to 30 000 years, which corresponds to the orbit size from several solar radii (solar radius is 700 000 km, or 7 x 10^{10} cm) to 0.005 pc (1 pc = 3 x 10^{18} cm, a bit less than distance to Proxima Centauri which is 1.3 pc). Noticeable fraction of them (about 1%) passes through a mass exchange at some stages of their evolution. This happens in two cases:

- When in the course of its evolution one of the stars increases its radius, or the system looses angular momentum and the orbit shrinks so one of the stars starts to fill its Roche lobe
- One of the stars passes through a very active phase, rejects its envelope through a stellar wind, and a fraction of this wind is intercepted by the companion.



Roche lobe/Hill sphere (wikipedia)





2. Binary stars

We will first consider the mass exchange mechanism, and later we will discuss the types of stars and evolutionary stages when this happens.

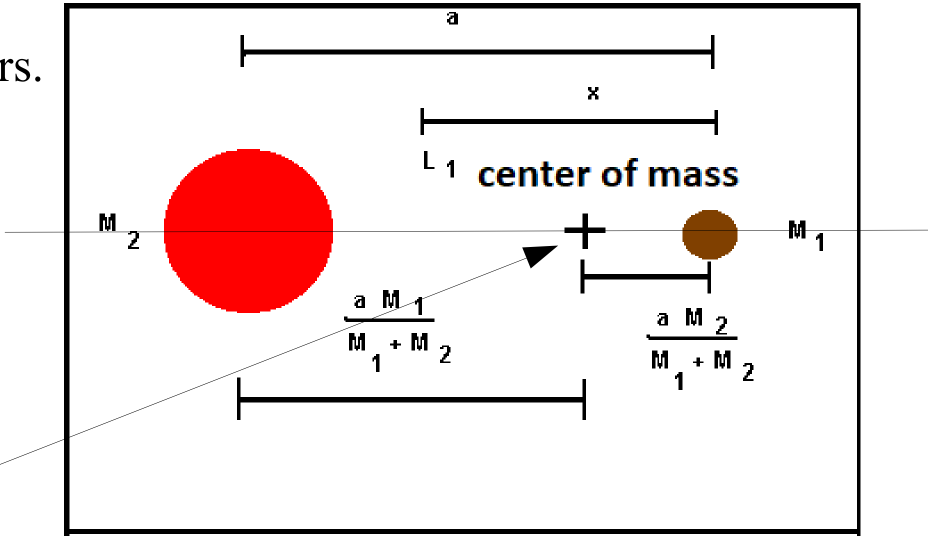
2.1 Mass exchange through L1

(a) Roche/Hill potential

We will consider the motion of a test particle in the gravitational field of two stars moving around themselves (or actually, around the center of mass) on circular orbits. We will assume that the two stars can be represented as point-like sources. This description is relatively good if the motion is synchronous.

We will consider in detail the forces acting along the line joining the two bodies. In general, 3-D considerations have to be performed.

Firs, we need a concept of a center of mass for the two stars.



According to *wikipedia,* the center of mass of a distribution of mass in space is the unique point where the weighted relative position of the distributed mass sums to zero. This is the point to which a force may be applied to cause a linear acceleration without an angular acceleration.

We will use coordinates at which the center of mass is at rest.

2.1 Mass exchange through L1

There is another important point along this axis, where the test particle is equally attracted to body 1 and body 2. However, the two bodies rotate, and we look for a particle which remains in its position on the axis, so it also in general will rotate, so in the co-rotating frame apart from gravity we will also have a centrifugal force.

Test particle of the mass m on a symmetry axis (rigidly rotating with the system) – balance of forces:

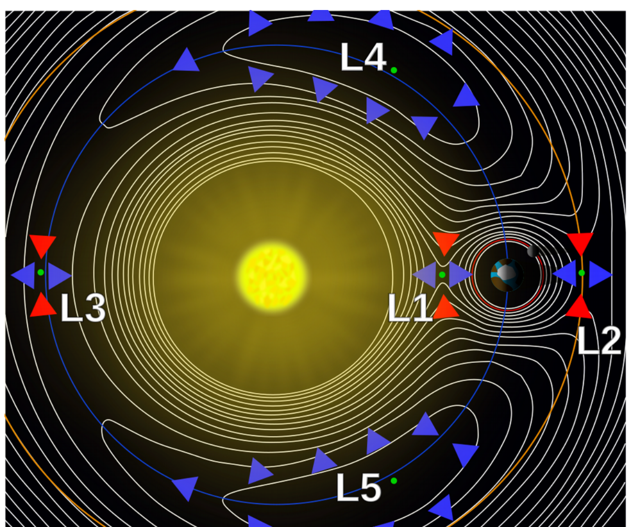
$$\frac{GM_2 m}{(a-x)^2} + m\Omega^2\left(x - a\frac{M_2}{M_1+M_2}\right) = \frac{GM_1 m}{x^2} \qquad (1)$$

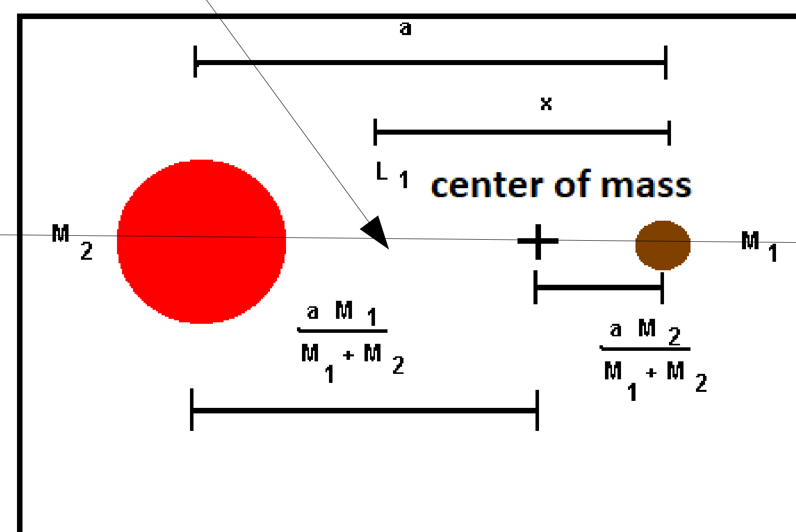
The angular momentum Ω is determined by the Kepler law

$$\Omega^2 = \frac{G(M_1+M_2)}{a^3} \qquad (2)$$

The equation has to be solved for x or (a – x) numerically.

Equations (1) and (2) determine the position of the inner Lagrange point L1





Points L1, L3 and L5 are unstable, points L4 and L5 are stable

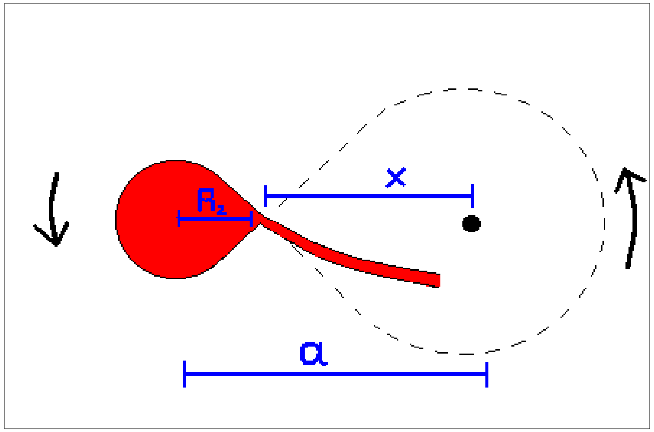
2.1 Mass exchange through L1

The inner Largange point L1 is unstable so if in the course of the evolution the star M_2 expands enough to fill its Roche lobe (the star radius becomes equal to a-x) and there will be a further rising trend, a mass flow will take place from the star M_2 to the star M_1. The precise description of the flow requires drawing the full topology of the equipotential surfaces. This is done by solving for the 3-D motion of the test particle:

$$\frac{\partial \vec{v}}{\partial \vec{t}} + (\vec{v}\nabla)\vec{v} + 2\Omega\times\vec{v} = -\nabla\phi_R$$

$$\Omega = \left[\frac{G(M_1+M_2)}{a^3}\right]^{1/2}\vec{i}$$

$$\phi_R = -\frac{GM_1}{|\vec{r}-\vec{r}_1|} - \frac{GM_2}{|\vec{r}-\vec{r}_2|} - \frac{1}{2}(\Omega\times\vec{r})^2$$



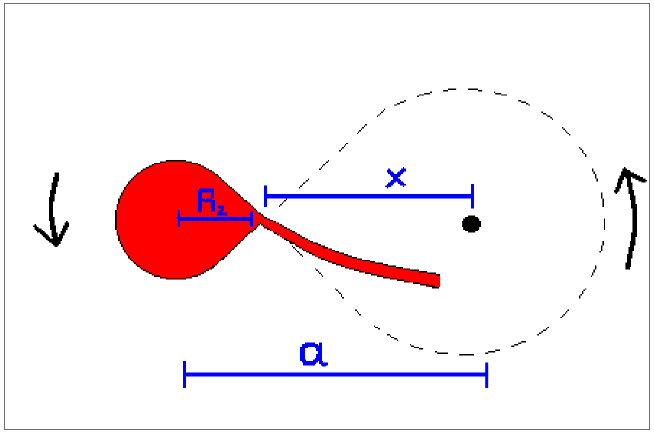
Here **i** is the unit vector perpendicular to the orbital plane, and vectors $\mathbf{r}_1$ and $\mathbf{r}_2$ determine the position of the stars. The picture shows the cross-section of the situation in the equatorial plane. The center of mass does not move, but the point L1 rotates. Thus the stream of the gas in general does not flow along the symmetry axis, and the stream motion is set by its angular momentum. If masses are equal, then the stream would be a straight line, since then L1 would be at the center of mass.

Detailed computations can be done numerically, but in many cases an approximate solution is good enough.

2.1 Mass exchange through L1

Assumptions:

- The size of the Roche lobe (i.e. the size of the star filling its Roche lobe) can be treated as a sphere with the radius:



$$\frac{R_2}{a} = 0.462\left(\frac{M_2}{M_1+M_2}\right)^{1/3} \qquad \textit{Paczynski}\ (1967)$$

This formula is a crude approximation, better approximation

$$\frac{R_2}{a} = \frac{0.49\,q^{2/3}}{0.6\,q^{2/3}+\ln\left(1+q^{1/3}\right)}; \quad q=\frac{M_2}{M_1}; \quad 0<q<\infty$$

was provided by Eggleton (1983) but we will use now the simplest version of Paczyński

- The motion of the stream can be approximated by the motion of a test particle.

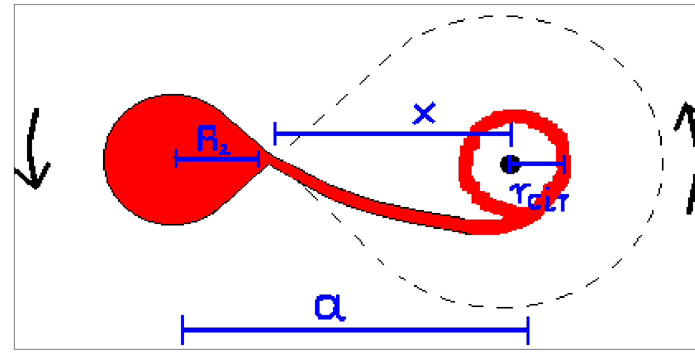
With this two approximations we will be able to derive the criterion for:

Condition for formation of an accretion disk around the compact star

The outflow proceeds with a super-sonic velocity, so the approximation of a test particle motion in a gravitational field is appropriate. Still, it is not simple to calculate the full orbit, but we can easily estimate the **circularization radius** r_{cir} which is defined as a radius of the circular orbit corresponding to the angular momentum of the flow; setting on the circularization radius usually requires getting rid of the excess energy by dissipation.

2.1 Mass exchange through L1

To get the circularization radius we need to calculate the angular momentum of the particle per unit mass with respect to the mass M1 and find the radius of the circular Keplerian orbit corresponding to that value:



$$\Omega x^2 = \Omega_K r_{cir}^2 \qquad \Omega_K = \left(\frac{GM_1}{r_{cir}^3}\right)^{1/2} \qquad a - x = a\frac{R_2}{a}$$

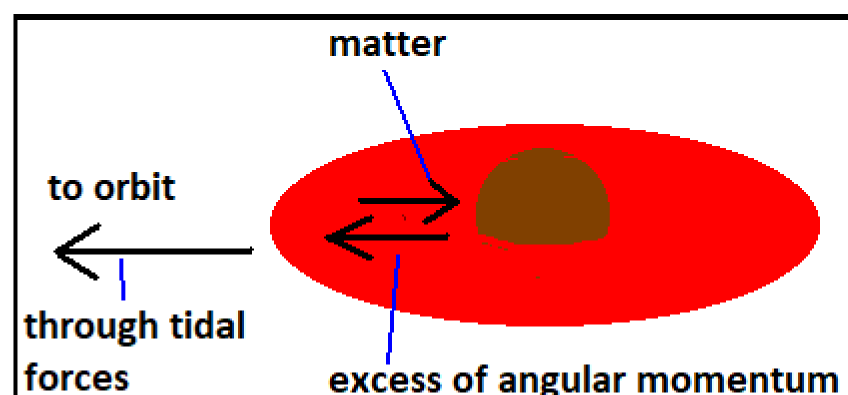
And from this equation we get the relatively simple formula

$$r_{cir} = a\frac{M_1+M_2}{M_1}\left[1-0.462\left(\frac{M_2}{M_1+M_2}\right)^{1/3}\right]^4$$

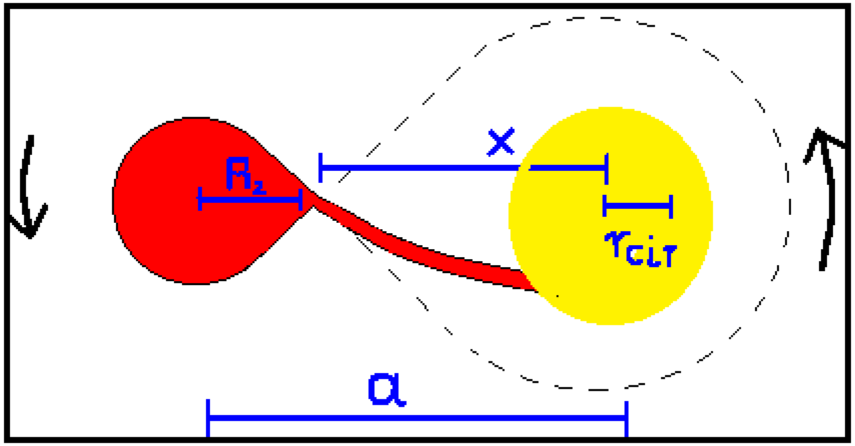
You can check that for typical masses in the X-ray binary systems the circularization radius is by a factor of 2-3 smaller than the Roche lobe size of the second star, x. The accreting matter will this form a ring if

$r_{cir} \gg R_1$ circularization radius is larger than the central star

If this condition is satisfied, the matter accumulates is a ring, and later, if the matter can redistribute the angular momentum through the action of viscous forces, the matter will drift towards the central star. An accretion disk will form. The matter will also spread a bit outward up to the radius where the angular momentum is extracted by tidal forces.



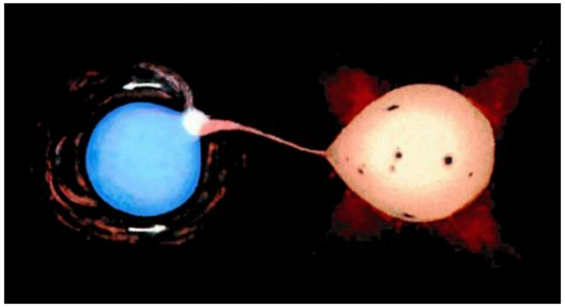
2.1 Mass exchange through L1



The condition is not satisfied if the M1 star is a main sequence star, and the period of the binary is shorter than 100 days. This is the likely situation in Algol-type binary stars. The accretion there does not lead to very efficient energy dissipation.

Interacting Binary Stars

Algol-Type Binaries



Geary E. Albright
SMP March 2, 2013

Binaries with one star filling the Roche lobe and the other one smaller are defined as semi-detached binaries.

Evolutionary effects – direction and timescales

The mass exchange changes the orbit since it changes M_1 i M_2.

We will consider a case of the conservative mass and angular momentum transfer, i.e. no mass or angular momentum are lost by the system of the two stars (a loss could be caused by wind, gravitational waves).

$$M_1 + M_2 = M = const$$ **mass conservation**

$$(M_1 a_1^2 + M_2 a_2^2)\Omega = J = const \qquad a_1 = a\frac{M_2}{M} \qquad a_2 = a\frac{M_1}{M}$$ **conservation of angular momentum**

2.1 Mass exchange through L1

The two conditions can be differentiated to see how the change in time proceeds. In particular, we can determine the direction of the change in the Roche lobe size of the star M2, the donor.

$$\frac{\dot{R}_2}{R_2} = -2\frac{\dot{M}_2}{M_2}\left(\frac{5}{6}-\frac{M_2}{M_1}\right) \qquad q=\frac{M_2}{M_1}$$

It is convenient to analyze what is happening by introducing the mass ratio, q.

$$\frac{\dot{R}_2}{R_2} = -\frac{2\dot{M}_2}{M_2}\left(\frac{5}{6}-q\right)$$

If **q is smaller than 5/6** the derivative the radius is negative (the sign of $\dot{M}_2$ is negative !), the Roche lobe of the star loosing mass expands, the star hides inside and stops loosing mass through L1. The mass exchange is stable since we have to wait for the evolutionary effect which are able to lead to the stellar radius expansion, the process happens in the star nuclear burning timescale.

If **q is larger than 5/6** the derivative of the radius is positive, the Roche lobe shrinks, the stellar radius exceeds the Roche lobe size and loose the mass from the envelope. The timescale of the mass loss is **rapid,** and it is then determined by the expansion timescale for the stellar envelope.

$q > \frac{5}{6}$ →

Radiative envelope - thermal timescale

Convective envelope - dynamical timescale

2.1 Mass exchange through L1

Thermal timescale for the Sun-like star:

$$t_{K-H} = \frac{GM_s^2}{R_s L_s} \approx 3\times10^7 \; years$$

and the corresponding accretion rate is

$$\dot{M} = \frac{M_1}{t_{K_H}} = 3\times10^{-8}\frac{R_1}{R_s}\frac{L_1}{L_s}\frac{M_s}{M_1} \quad [M_s/yr] \qquad [i.e.\;\; 2\times10^{18}\, g/s]$$

Dynamical timescale for the Sun:

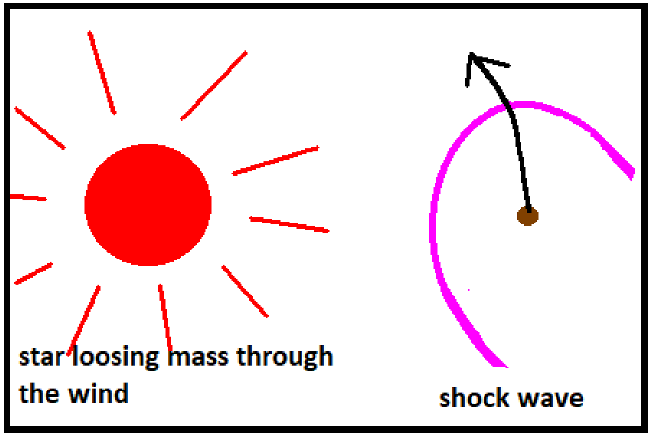
$$t_{dyn} = \frac{1}{\Omega_K} = \left(\frac{R_s^3}{GM_s}\right)^{1/2} \approx 14\,h$$

In such case the accretion rate is far above the Eddington rate.

$$\dot{M} = \frac{M_1}{t_{dyn}} = 6\times10^3\frac{R_s}{R_1}\frac{M_1}{M_s} \quad [M_s/yr] \qquad [i.e.\;\; 4\times10^{29}\, g/s]$$

2.2 Accretion from the stellar wind

If the binary star contains a massive O or B type star, or evolved type M giant then the star is a source of strong supersonic stellar wind. The star mass loss is of order of 10^{-6} - 10^{-5} Ms/year, but only a small fraction of this wind, usually 10^{-4}-10^{-3}, is intercepted by the companion. Computations are complex, the possibility of the accretion disk formation dramatically depends on the wind velocity: $r_{cir} \sim 1/v^8$.



2.3 Evolution and accretion phases in binaries

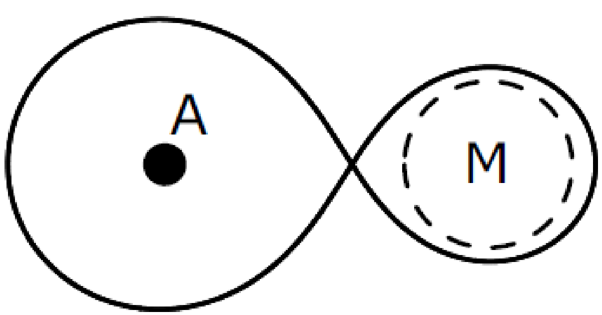
Evolution of the binaries sometimes consists of two phases of mass exchange.

In particular, we will discuss later in much detail compact binary systems: low mass X-ray binaries and cataclysmic variables since there the accretion disk structure is relatively well understood, and they are great astrophysical laboratories for the theory. Those systems are in the second phase of mass exchange.

First episode of the mass exchange

The star more massive of the two evolves faster. At the early stage $q>1$.

Long accretion episode: a giant M-type star + main sequence star; they form still a detached system, the accretion proceeds through a wind mechanism. Some symbiotic stars look like that.



Shorter episode: if the M-star finally fills its Roche lobe the system becomes a semi-detached binary. The situation strongly depends on the exact evolutionary stage of the star M, which in turn is set by the initial masses and initial orbital period.

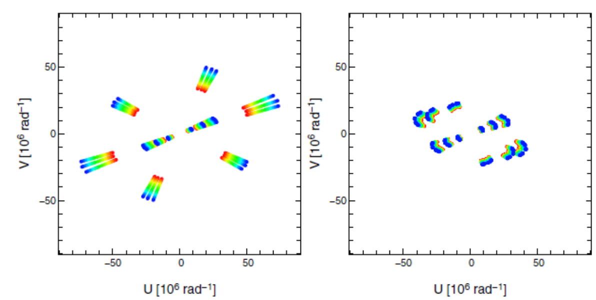
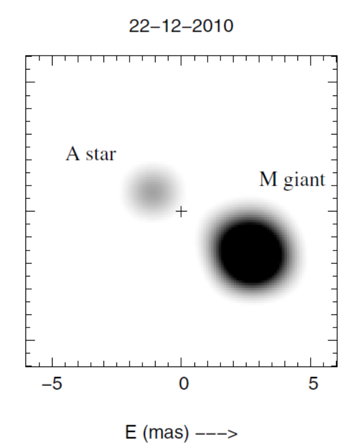


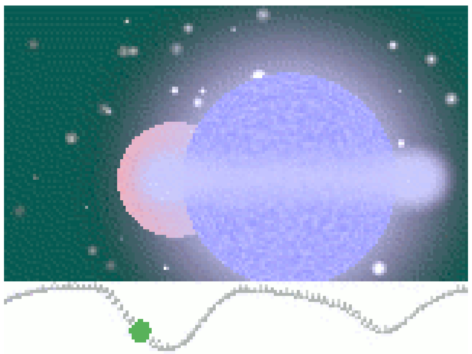
Fig. 1. Typical *(u,v)*-plane coverage for AMBER (*left*, November 2008) and PIONIER (*right*, October 2010) observations.



SS Liporis - milli-arcsecond imaging with PIONIER/VLTI, Blind et al. (2011)

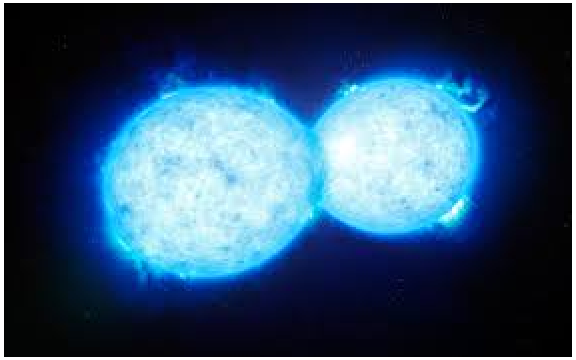
2.3 Evolution and accretion phases in binaries

Case A: the envelope is radiative, so the evolution proceeds in thermal K-H, with a strong departure of the star structure from thermal equilibrium, till finally the system achieves the inversion of the mass.
After that the mass flow slows and proceeds further in the semi-detached geometry, but now in nuclear timescale.
The transition characterizes by a clear change of the orbit, for example beta Lyrae star is at that stage (P/Pdot $\sim 10^5$ years). Such systems are numerous, and further evolution may lead to formation of a contact binary.



Left: snapshot from the movie illustrating the structure of beta Lyrae-type star and its eclipses (Polish wikipedia)

Right:contact binary (illustration), wikipedia



Case B1: later stage contact: initially evolution again in the thermal K-H timescale, further stage also in a thermatimescale but different due to the change of the stellar structure: contraction of the helium nucleus and expansion of the envelope

$M > 3M_s$ star stars to burn helium, later evolution in the nuclear timescale (Wolf-Rayet star)

$M < 3M_s$ nucleus stops contracting due to the pressure of degenerate electrons (like in a white dwarf), the burning proceeds only in the envelope, the evolution in the nuclear timescale proceeds (Algol system), finally a white dwarf forms but on the large radius orbit.

Case B2 i C: star with the convective envelope, mass exchange in the dynamical timescale, Mdot >>MdotEdd. Just before the contact we may have a stage of a symbiotic star (e.g.. CI Cyg). If $M_2/M_1 < 0.28$ is a giant when it starts to fill its Roche lobe, this evolutionary path will lead to the formation of a cataclysmic variable, important in the further parts of the lecture series.

A white dwarf forms, the small size of the star hides it deeply inside its Roche lobe and the contact is lost. But the dynamical mass exchange episode leaves its signature.

2.3 Evolution and accretion phases in binaries

The key problem is to get the systems which we will use later for accretion disk studies, There are Low Mass X-ray binaries and cataclysmic variables. Their orbits are small in comparison of the solar radius. They could not have been born like that. The initial separation was much, much larger! The most extreme case (with a white dwarf companion !) has the orbital period 11 minutes.

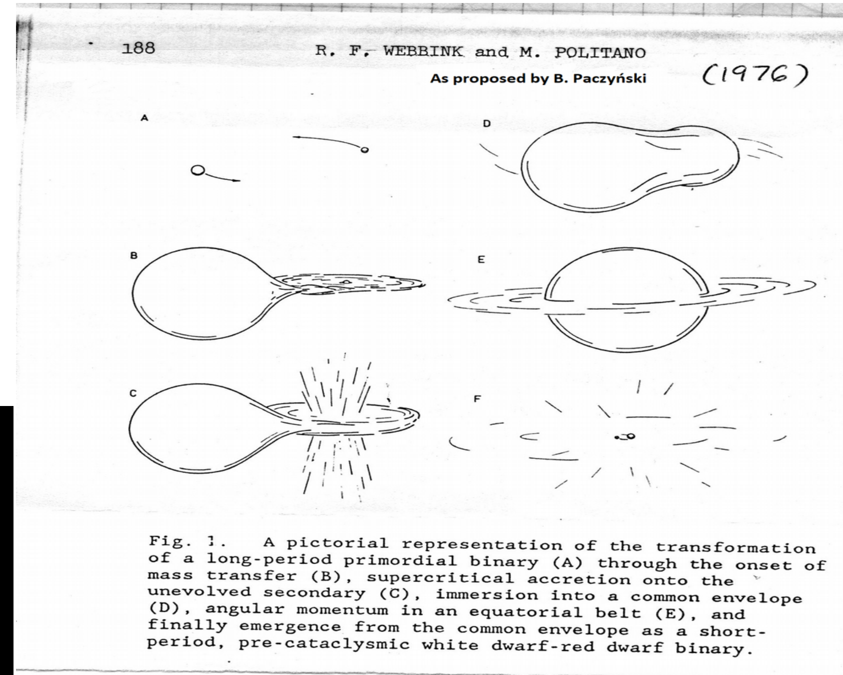
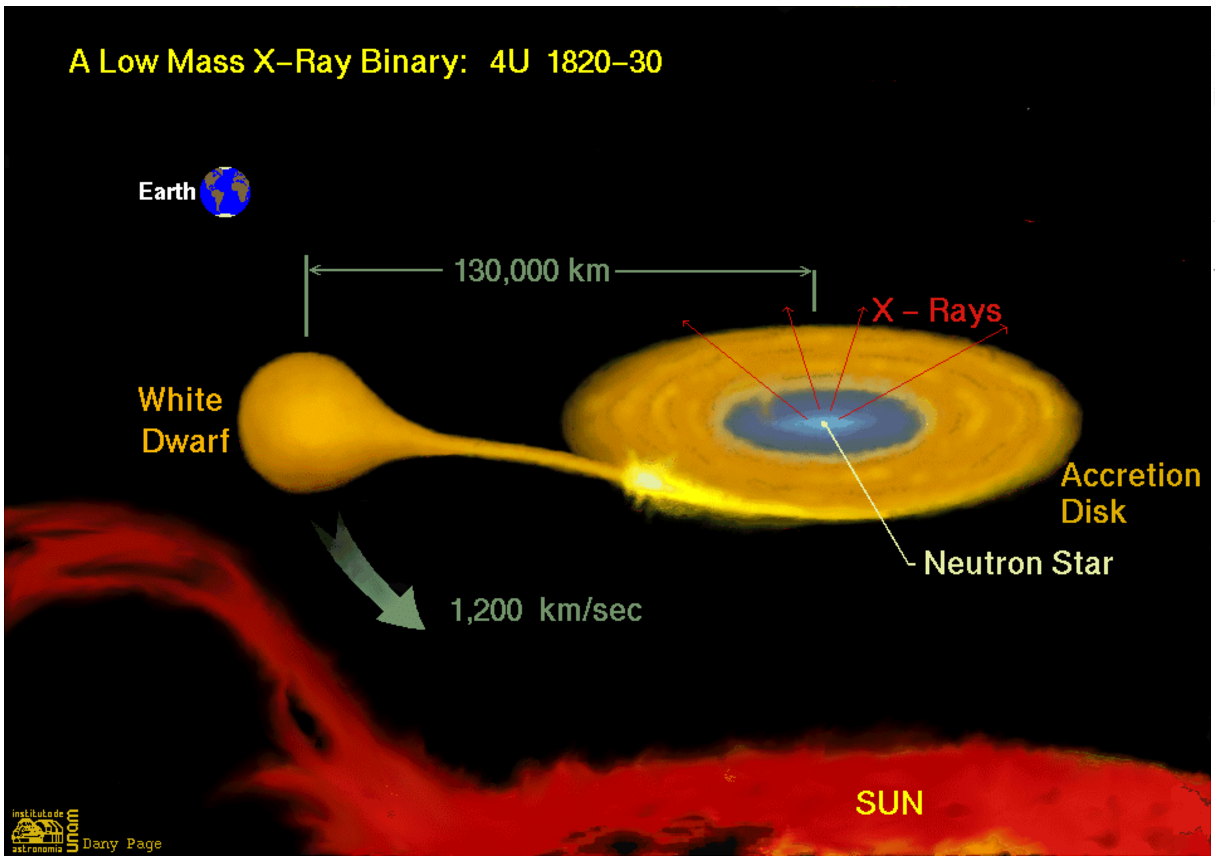


Fig. 1. A pictorial representation of the transformation of a long-period primordial binary (A) through the onset of mass transfer (B), supercritical accretion onto the unevolved secondary (C), immersion into a common envelope (D), angular momentum in an equatorial belt (E), and finally emergence from the common envelope as a short-period, pre-cataclysmic white dwarf-red dwarf binary.



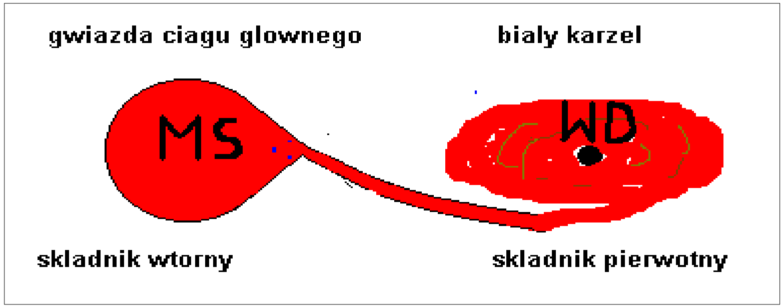
Dany P. Page
http://www.astroscu.unam.mx/neutrones/NS-Picture/1820-30/1820-30.html

A solution has been proposed many years ago, and the name of the solution is **common envelope phase.** For example the plot above shows one of the earliest illustrations of what must have happened. It concentrates on the formation of a system with a white dwarf (cataclysmic variable) consisting of a white dwarf and a low mass main sequence star (red dwarf) on a compact orbit. If the initial mass M_1>10-12 M_s then instead a white dwarf we get a neutron star or even a black hole (low mass X-ray binaries).

2.3 Evolution and accretion phases in binaries

The exact detail of the formation, particularly the common envelope phase and the surviving the Supernova outburst by the system is till under discussion, and many details are not known.

One way or another we must end up with a main sequence low mass star, and a compact object at a relatively tight orbit, with orbital periods typically of order of days. Initially the stars are detached.

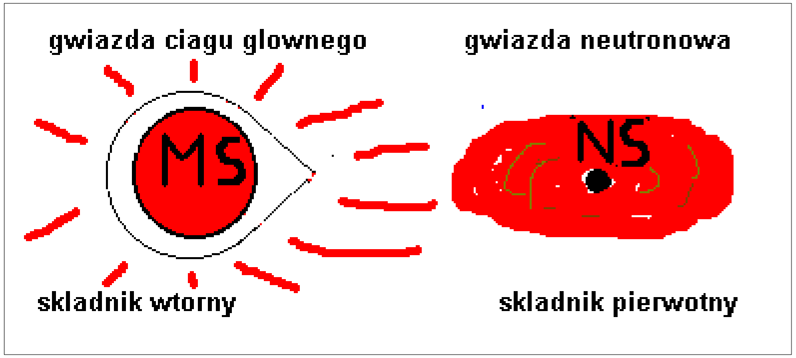


Compact object: white dwarf, neutron star or a black hole, accretion through L1 or from the wind.

Second mass exchange phase

Next, after a long evolution, stars come again into the contact, but now in this **secondary contact,** their roles is now changes, the non-evolved star, initially M2, now provides the mass.
The tightening of the orbit is the result of

(a) gravitational radiation
(b) magnetic braking, i.e. the loss of angular momentum from the system due to the magnetized stellar wind carrying angular momentum.



The estimate of the magnetic braking is not simple, but the gravitational wave mechanism must work and the binary evolution was one of the first evidences for the existence of gravitational waves (Paczynski, B. Sienkiewicz, R. 1981), the results from the Hulse-Taylor pulsar came the same year.

Low-mass X-ray binaries NS+MS probably form in the couse of accretion onto the white dwarf which finally collapse after crossing the Chandrasekhar limit
$M_{WD} < 1.4\ M_s$
Resulting from the pressure of degenerated electrons.
SN Ia outburst mechanism !

3. Active galactic nuclei – source of material

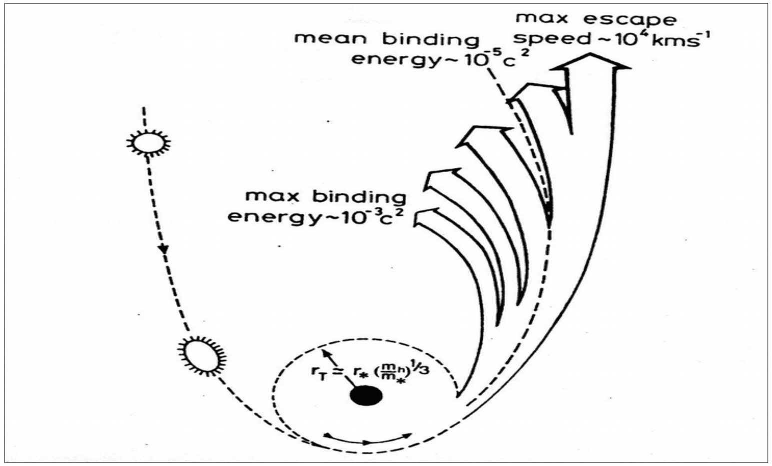
In the case of AGN we do not have a second star – donor – and we need in some cases (quasars !) a lot of material. Many quasars radiate close to the Eddingon luminosity, have luminosities of order of 10^{47} erg/s, and to provide this luminosity we need a mass flux of order of one solar mass per year. What can we have?

1. infall of a star towards the galactic center

Stars are usually on very stable orbits, and they have large angular momentum which prevents them to fall in (e.g. Solar System and the Milky Way). This is why galaxies exist for billions of years. But sometimes a star can approach the central black hole

1a. sporadic accretion

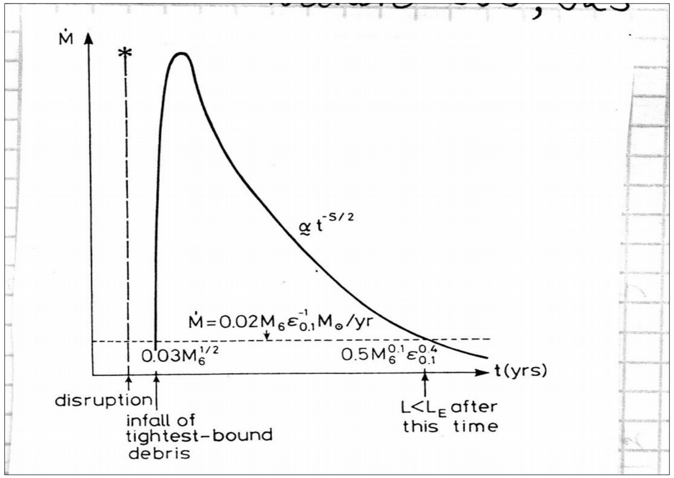
Rare cases happen. The mechanism was proposed by Hills (1975), and elaborated in much detail by Rees (1988). Rees estimated that in typical galaxies this may happen once in every 10^4 years. So this is not for quasars but good enough to reactivate non-active galaxy for some time. If the main sequence star passes close to the black hole, and the black hole is not too massive (mass below 10^8 Ms), the star will be disrupted by the tidal forces. About half of the material will escape, carrying excess angular momentum, and half will settle onto an elliptic orbit later forming an accretion disk.



The event will last about a year (from Rees 1988).

$$\rho_{star} < \frac{M}{R^3}$$

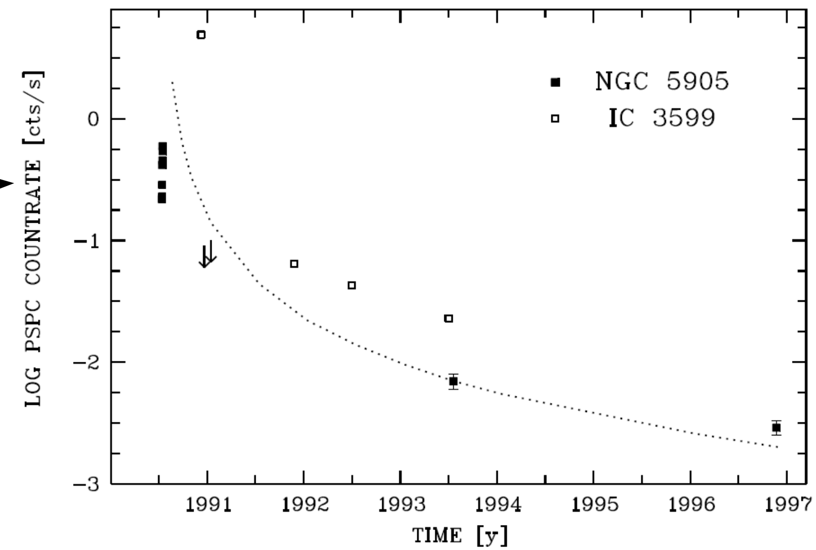
Criterion for stellar disruption



3. Active galactic nuclei – source of material

More massive black holes will not disrupt the star, no clear signal expected.

First detection – Komossa & Bade (1999), detection in X-rays. Now we have at least 40 cases of stellar disruptions, some of the events are seen in gamma-rays and are accompanied by a jet formations (first case: Swift J164449.3+573451).

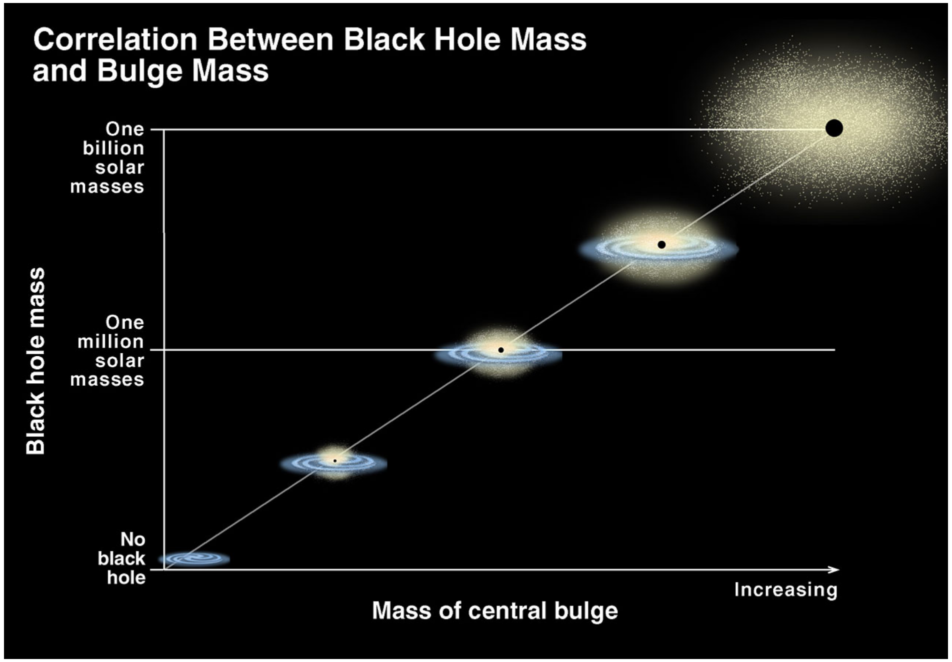


1b. massive accretion due to galaxy mergers ?

Galaxies in the course of their evolution merge. Milky Way will likely consume Magellanic Clouds. Merger causes the drift of the material (stars and gas) towards the center, tidal forces and local gravitational instabilities are important but details not well established.
The co-evolution of the galaxy and the central black hole is seen statistically through the Magorrian relation

$$M_{bh} \approx 0.0014\, M_{bulge}$$

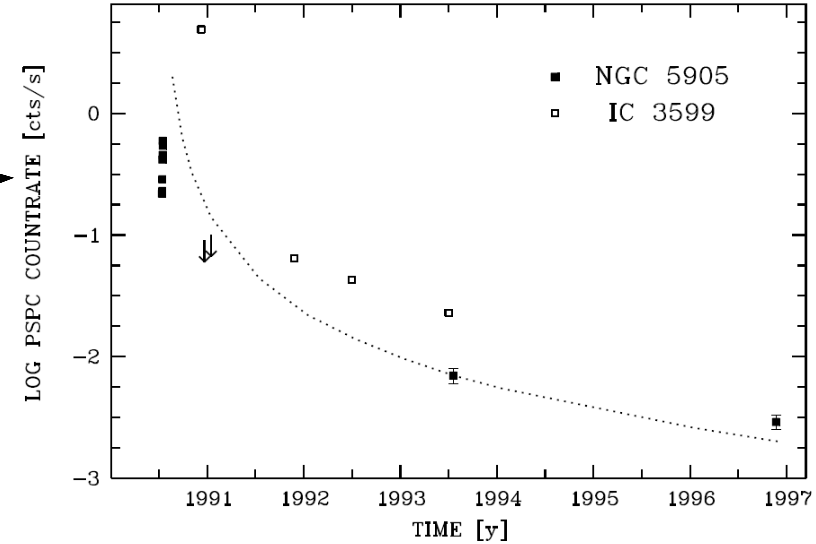
We still do not know if this is caused by mergers or by AGN/star formation feedback. And the data points show large dispersion.



3. Active galactic nuclei – source of material

More massive black holes will not disrupt the star, no clear signal expected.

First detection – Komossa & Bade (1999), detection in X-rays. Now we have at least 40 cases of stellar disruptions, some of the events are seen in gamma-rays and are accompanied by a jet formations (first case: Swift J164449.3+573451).

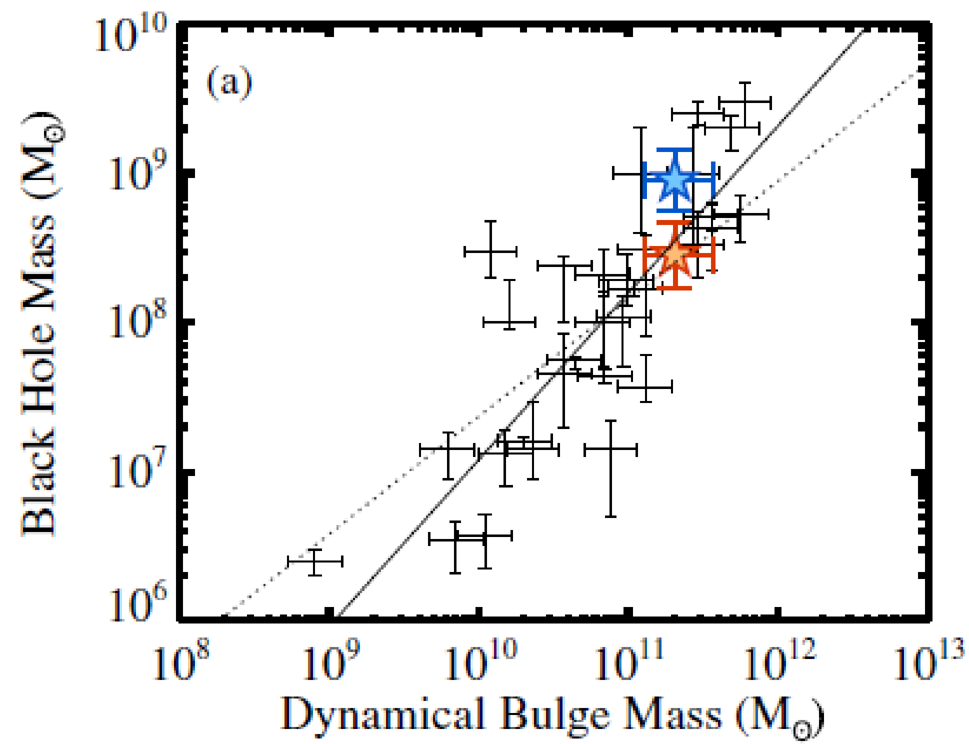


1b. massive accretion due to galaxy mergers ?

Galaxies in the course of their evolution merge. Milky Way will likely consume Magellanic Clouds. Merger causes the drift of the material (stars and gas) towards the center, tidal forces and local gravitational instabilities are important but details not well established.
The co-evolution of the galaxy and the central black hole is seen statistically through the Magorrian relation

$$M_{bh} \approx 0.0014\, M_{bulge}$$

From Inskip et al. (2011), also mentioned at lecture 2



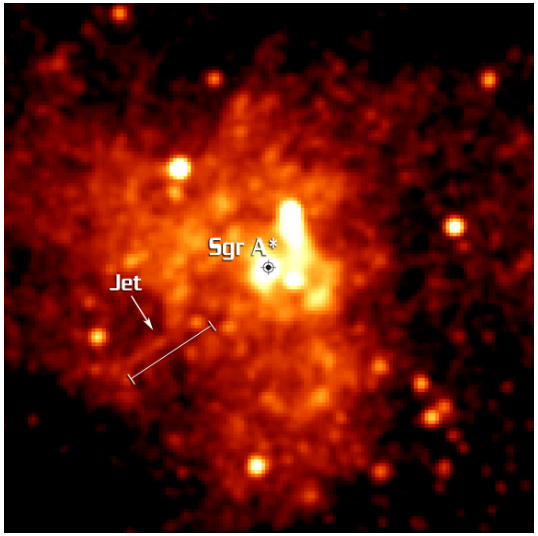
We still do not know if this is caused by mergers or by AGN/star formation feedback. And the data points show large dispersion.

Important: accreting matter is always of high (solar or super-solar) metallicity, even for quasars at z = 7.5. This material had to be processed efficiently by stars.

3. Active galactic nuclei – source of material

1c. hot accretion ?

Observations show that the galactic nuclei are filled by the X-ray emitting hot plasma. We see the hot plasma even at clusters of galaxies, as an Intercluster medium. This plasma, in principle, can cool an settle onto the nucleus and since it most likely is not rotating there is no angular momentum barrier.
It may be a source of accreting material, particularly in elliptical galaxies. We will talk about this accretion mode in one of the next lectures. But the inflow is not guaranteed. In Milky Way most of the hot material flows out (theory).



Chandra image of Sgr A region (size 3 pc, Credit: NASA/CXC/MIT/F.K. Baganoff et al.)*

2. Observational evidences of the cold gas inflow

It seems that cold inflow is most convenient to power an AGN but we still have very limited direct arguments for its existence. Some inflow is detected at the halo scale in distant galaxies (iflow from the intergalactic streams). Closer in there are numerous studies of the cold gas dynamics (molecular lines allow to see the radial velocity). But we see mostly rotation and outflow.

2a. NGC 1068 w podczerwieni i nadfiolecie

D ~ 18 Mpc, a Seyfert 2 galaxy. We see large amounts of material emitting in the IR and in the UV(side picture; Neff i in. 1994, ApJ, 430, 547) responsible for the strong starburst. All that at a distance of ~ 1kpc from the black hole (assuming black hole mass 10^8 $M_s$this is 10^8 Rs_{chw}).
Here we have a map, no velocity measurement.

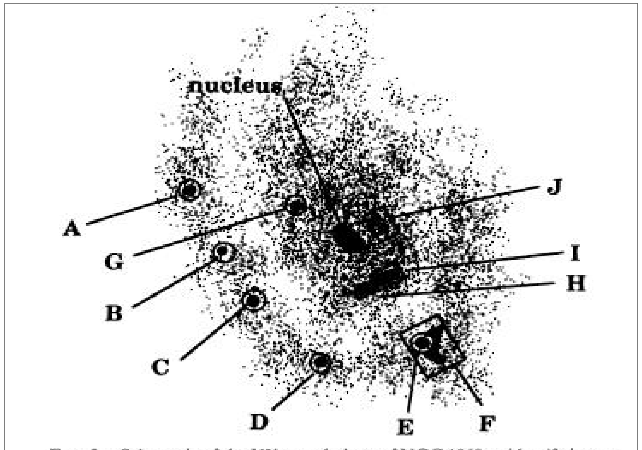
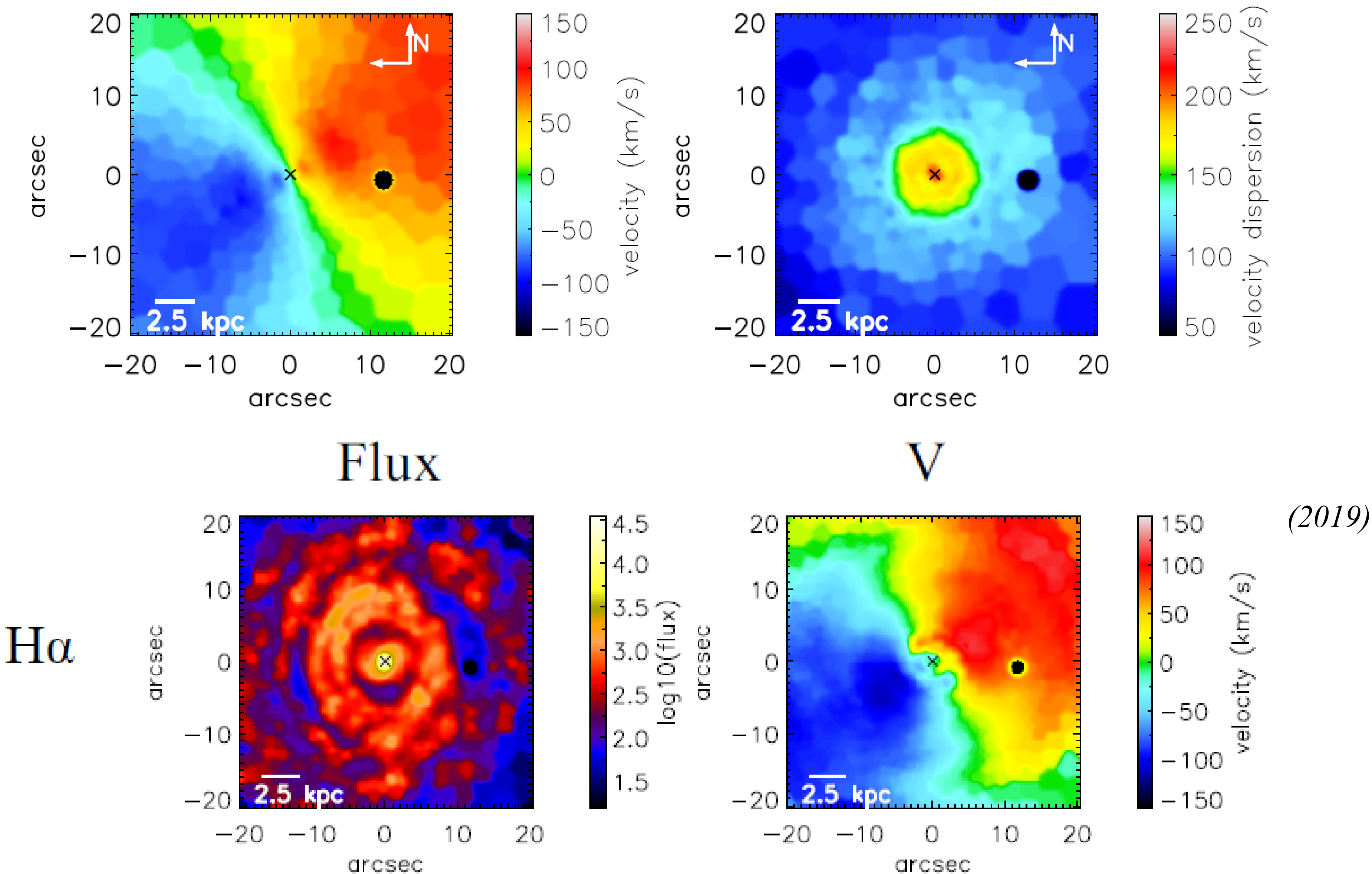


FIG. 3.—Schematic of the UV morphology of NGC 1068 to identify important features. The most prominent knots are labeled A–J, their (FUV – NUV) colors are given in Table 2.

3. Active galactic nuclei – source of material



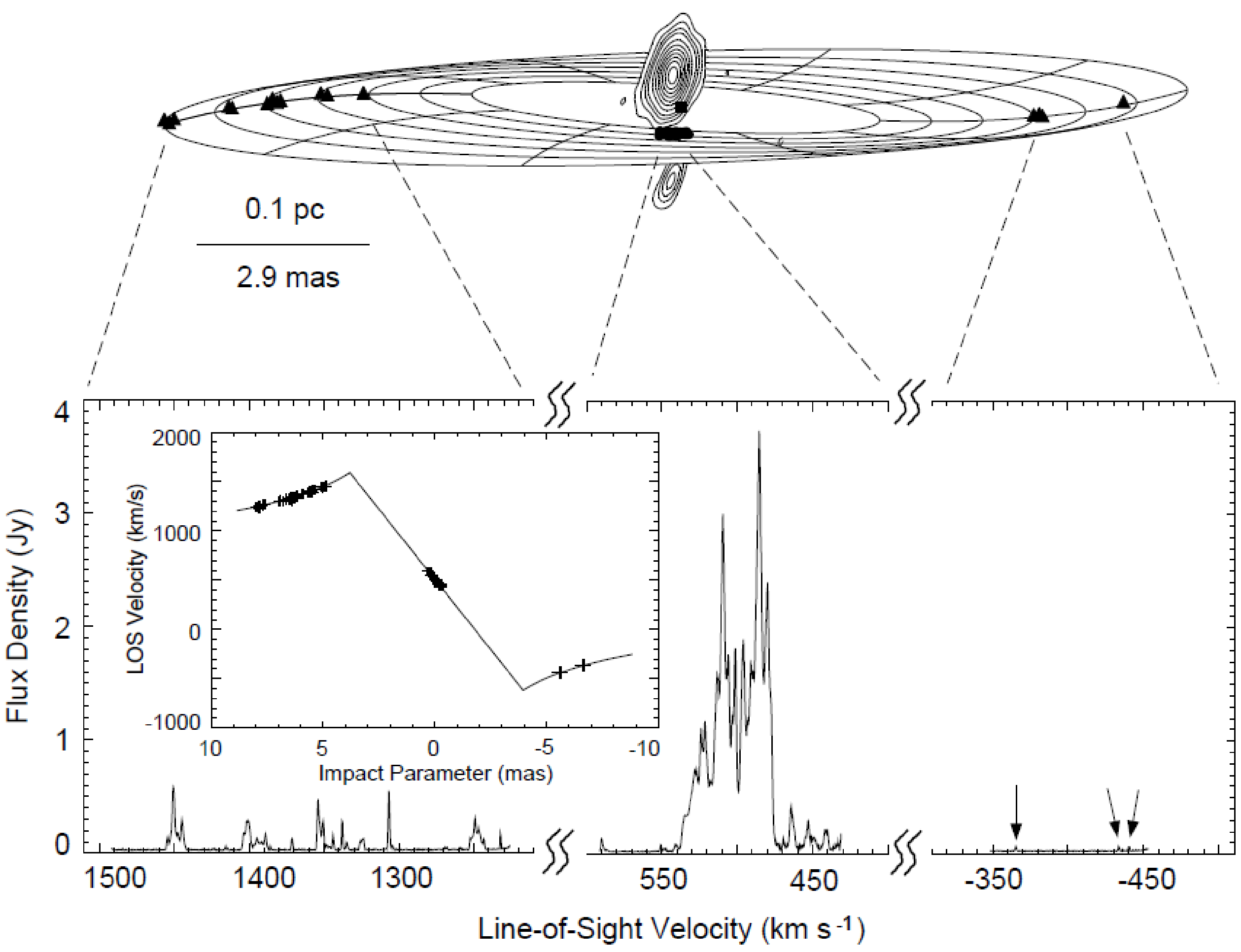
2b. Mkn 590 multi-wavelenght study, including MUSE (optical integral-field spectrograph on VLT)

D ~ 115 Mpc, changing-look AGN. Stellar motion implies just rotation (picture above), emission lines as well. H_2 map suggest a spiral shape of the mass reservoir (*From Raimundo et al. 2019*).

3. Active galactic nuclei – source of material

2c. water maser

This radio emission (observed at 22 GHz) is observed in NGC 4258 and several other active galaxies. Interferometric measurements allow to see the velocity field of the material at a fraction of a parsec.
The results imply that we observe a slightly warped disk with small deviations from the circular orbits.



We again see Keplerian motion, not an inflow.

This allows to measure the distance to the source directly (not from Hubble law), implications for H0 determination and cosmology.

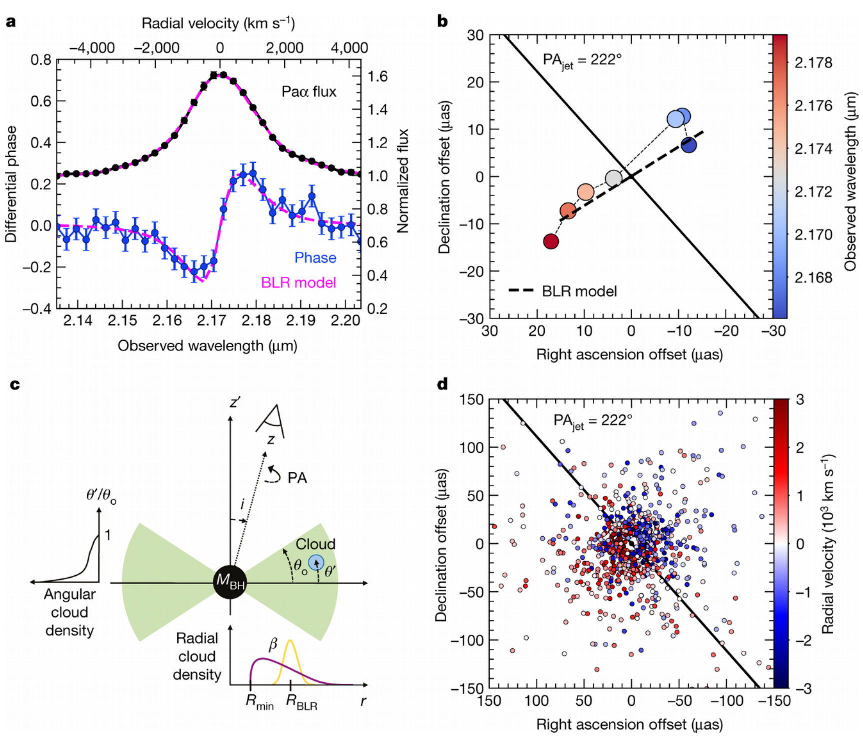
Herrnstein et al. (1999).

3. Active galactic nuclei – source of material

2d. Broad line Region

Broad emission lines are the most characteristic properties of the strong nuclear activity. The Broad Line Region (BLR) is located at a fraction of a pc from the nucleus (as measured from the time delay). Lines again are predominantly in Keplerian motion, occasionally outflow is seen, some (weak) arguments for inflow, based on the line shapes.

As mentioned in the Lecture 2, for the first time this region was resolved in a bright AGN 3C 273



Resolving Broad Line Region with GRAVITY on VLT in near-IR

Again, we see Keplerian motion, not an inflow.

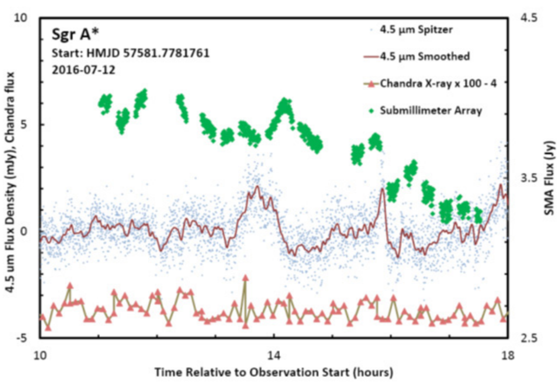
Why we never see clearly the inflow? Most likely because the inflow velocity is much smaller than the ouflow

Summary: we have no idea how AGN are powered, what determined the dusty cycle etc. But it must be related to star forming activity, with some delay.

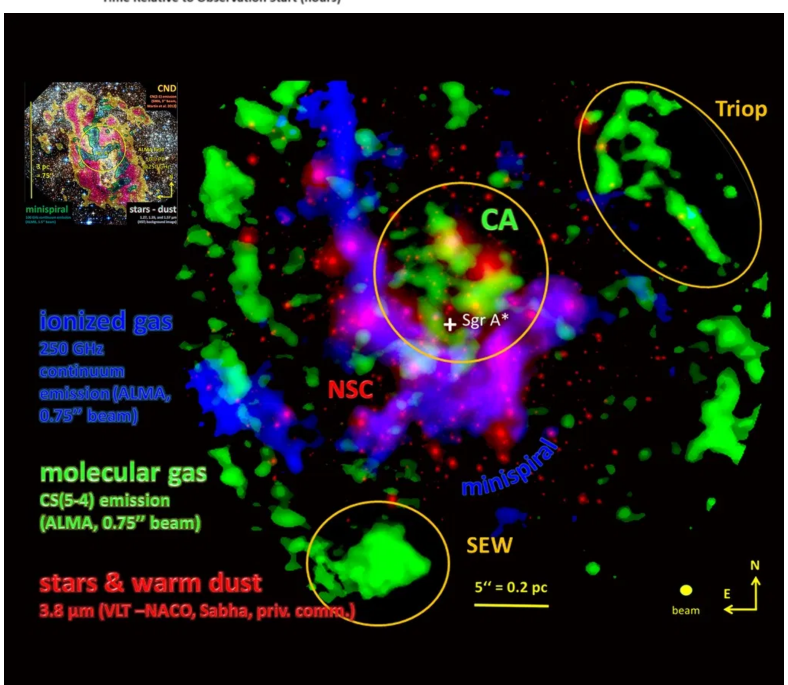
3. Active galactic nuclei – source of material

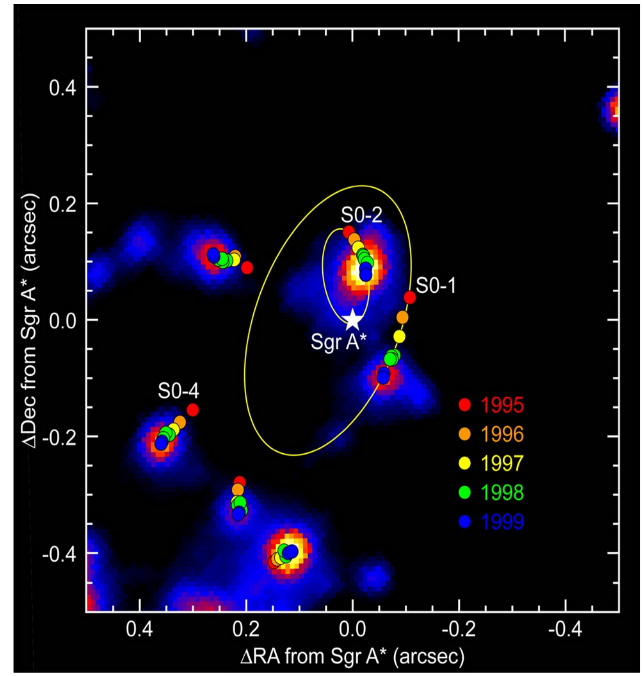
3. Problem of the feeding of the Milky Way center Sgr A*

The detection of the central black hole is unquetsionable, stars on close orbit allow to measure the black hole accurately, mass is 4.0 x 10^{6} Ms. It has the mean luminosity of about 10^{-9} L_{Edd}. Its weak activity is in a form of flares (e.g. Fazio et al. 2018, below).



Below: the nuclear region of Sgr A (Moser et al. 2017)*





Motion of stars aroung Sgr A (Ghez et al.)*

There is a ring of gas at the distance of about 1 pc but this gas does not reach now the black hole. There are gasous streams known as mini-spiral, their age in about 10 000 years, they formed out of the more distant circumnuclear ring. As was mentioned in Lecture 1, in the past Sgr A* was much more active but we do not know how this material reached the black hole vicinity.

3. Active galactic nuclei – classification

Since we have no clue about the feeding of AGN we have to relay on observations in AGN classification.

- **AGN**
  - radio-loud/jetted
    - RL quasars (bright)
    - Radio-galaxies (less bright)
  - radio-quiet/not-jetted
    - RQ quasars (bright)
    - Seyfert galaxies quasars (less bright)
      - NLS1 1 (Narrow Line Seyfert 1) galaxies
      - Seyfert 1 galaxies
      - Seyfert 2 galaxies
    - LINERS (Low Ionization Nuclear Emission-line Region - still less bright)

Besides those, there are blazars, BL Lacs, Weak Line Quasars, true Seyfert 2 galaxies, Changing-Look AGN ….

Homework

1. derive theequation for the derivative of the Roch lobe radius

$\dot{R}_2 \quad = \quad \ldots$

2. derive the formula for the condition of the tidal disruption of a star by a black hole

$\rho_{star} \; < \; \ldots..$