BLACK HOLE ASTROPHYSICS

2013/08/15

WE WILL COVER…

- 3. Microquasars: Black Holes and Neutron stars of Stellar Mass in Our Galaxy
  - 3.1 Isolated Neutron Stars: Pulsar and Magnetars
    - 3.1.1 “Normal” Pulsars
    - 3.1.2 Magnetars
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NEUTRON STARS

- Neutron stars are "near-black" holes, composed primarily of neutrons throughout much of the star's interior, with a gravitational field nearly as strong as that of a true black hole
- A neutron star of $1.5\ M\downarrow\odot$ has a radius of $10\ km$, while a black hole of the same mass would be about $4.5\ km$ in radius
- Both can produce X-rays when matter accretes onto them, but they do not do so in quite the same way
- However, a neutron stars still have a solid surface while the black hole do not
- Heat radiation produced by accretion must eventually escape a neutron star's solid surface, but a black hole can swallow it

NEUTRON STARS

- In 1962, it was suspected that the X-rays in these sources were produced by such accretion onto very compact objects
- However, since the resolution of X-ray telescope is poor, it can not identify the optical counterparts for the X-ray sources for any possible companions to be examined
- In 1964, the Crab Nebula was discovered to be an extended and steady X-ray source
- In 1968, Antony Hewish, S. Jocelyn Bell, and their colleagues at Mullard discovered pulsations coming from a compact star near the center of the nebula, once every 1/30th of a second
- This pulsar was soon identified as an isolated spinning neutron star, with the radio pulses coming from its magnetic field of $10^{13}\ G$

BLACK HOLES OF STELLAR MASS

- In 1960s, the USA launched two Vela satellites to search for γ-rays from terrestrial explosions in order to monitor the 1963 nuclear test ban treaty
- However, the satellites did not detect any γ-ray from the earth, but did from the cosmos
- In the late 1960s, these GRBs were determined to be the most powerful objects in the universe, even outshining the brightest quasars by tens of thousands of times for a few brief seconds.
- And GRB represents the celestial herald of the birth of a stellar-mass black hole

PULSARS

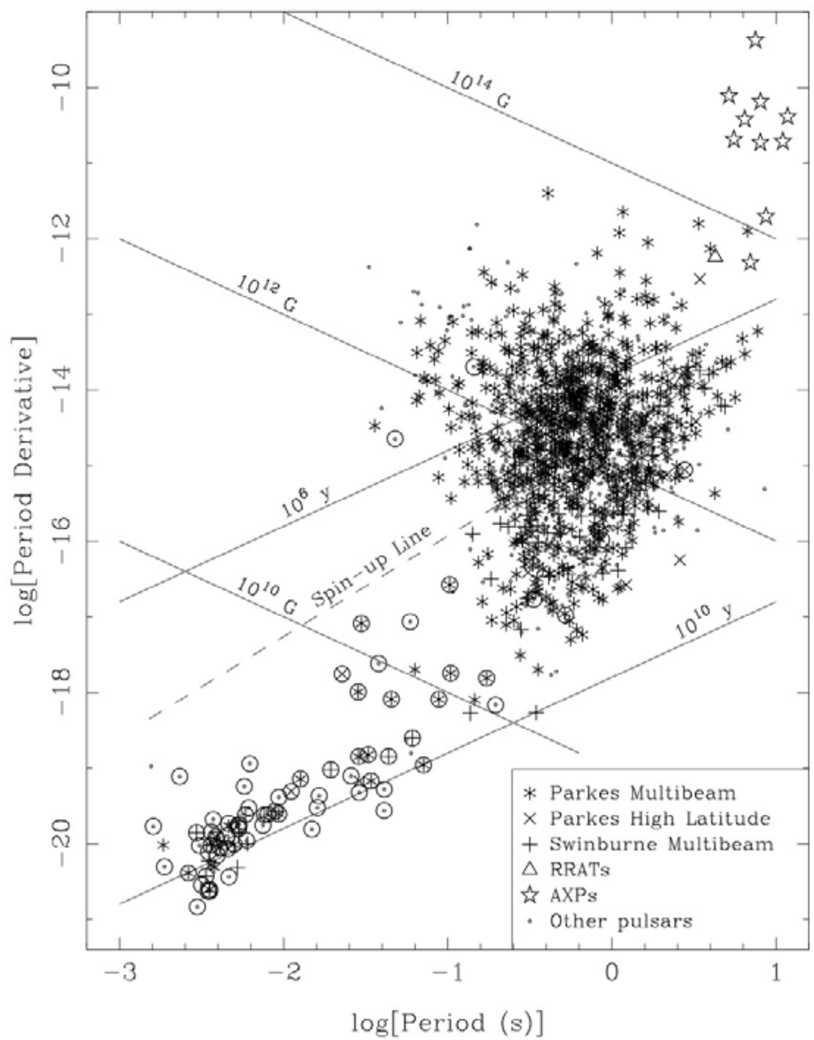
- Can range in period from several seconds to a millisecond
- Have extremely well-defined pulse periods
- Periods increase very gradually as the pulses slow down, the spindown rate is very low ($\sim 10^{-15}$)
- With sub-millisecond timing, the pulse periods accurate to better than a femtosecond (10^{-15} s)
- This highly accurate timing will allow pulsars to be used as aids to gravitational wave detection

PULSARS

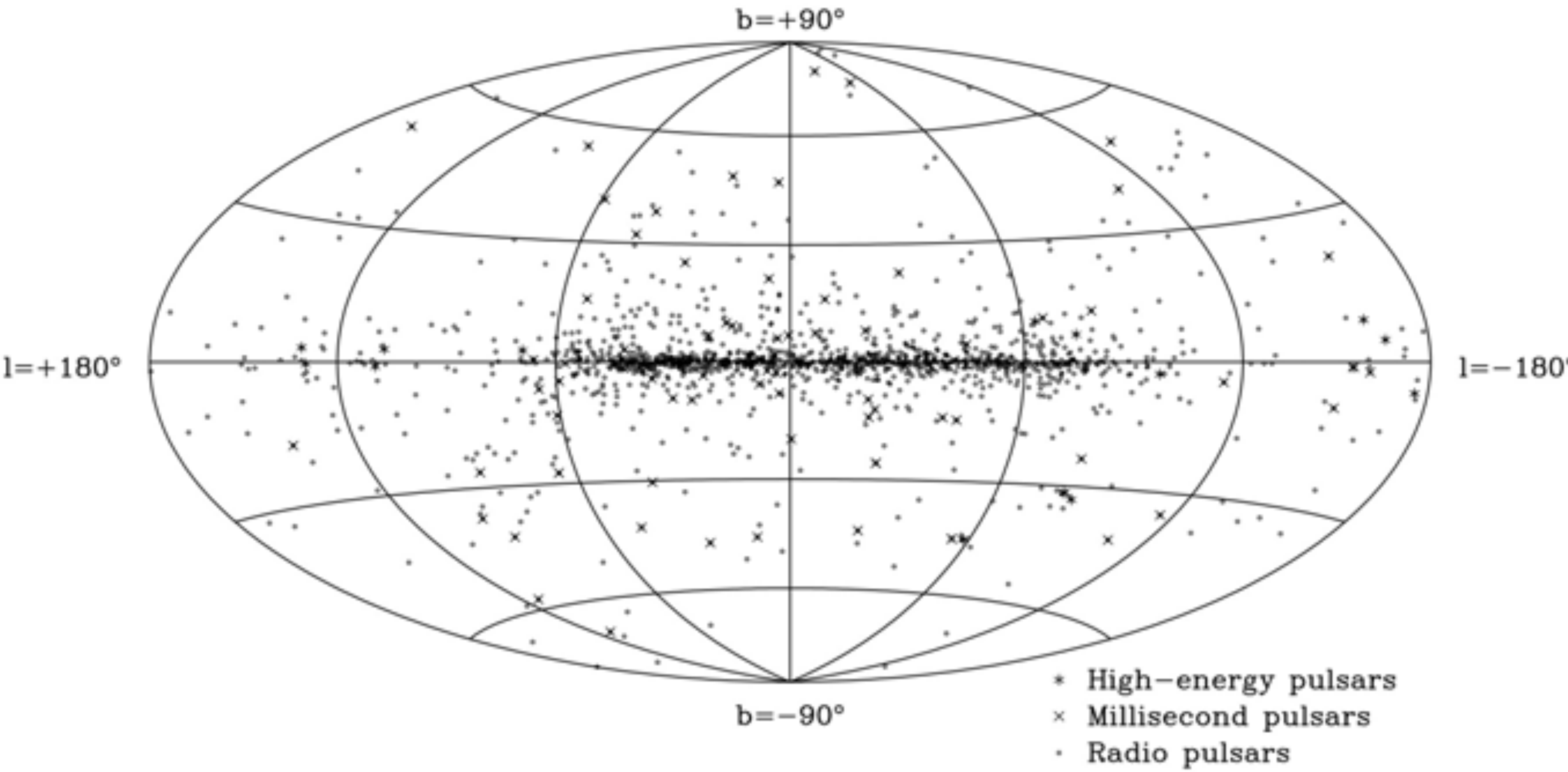
- Approximate distances to pulsars are measured by measuring the "dispersion"
- $D = 240 pc \frac{\Delta t_{12}}{\langle n_e \rangle} \frac{1}{\nu_1^{-2} - \nu_2^{-2}}$
- The period and spindown rate can also be used to estimate the pulsar's age and the neutron star's surface magnetic field
- $\tau = P/2P$
- $B = 3.2 \times 10^{19}\ G\ (PP)^{1/2}$
- Using these expressions, the Crab Pulsar ($P = 0.033\ s$ and $P = 4.23 \times 10^{-13}$) has a characteristic age of $\tau = 1200\ yr$ and a magnetic field of $3.8 \times 10^{12}\ G$
- Close to the real age $950\ yr$

PULSARS

- The $P-P$ plane for all radio pulsars in the Galactic plane known in 2007
- The Crab is a young member of the class of “normal” pulsars, which occupy the large collection of objects in the middle-right portion of the diagram, which are the “normal” pulsars
- $P = 0.1 - 3.0\ s$
- $P = 10^{-17} - 10^{-13}$
- $\tau = 10^{5} - 10^{8}\ yr$
- $B = 10^{11} - 10^{13}\ G$

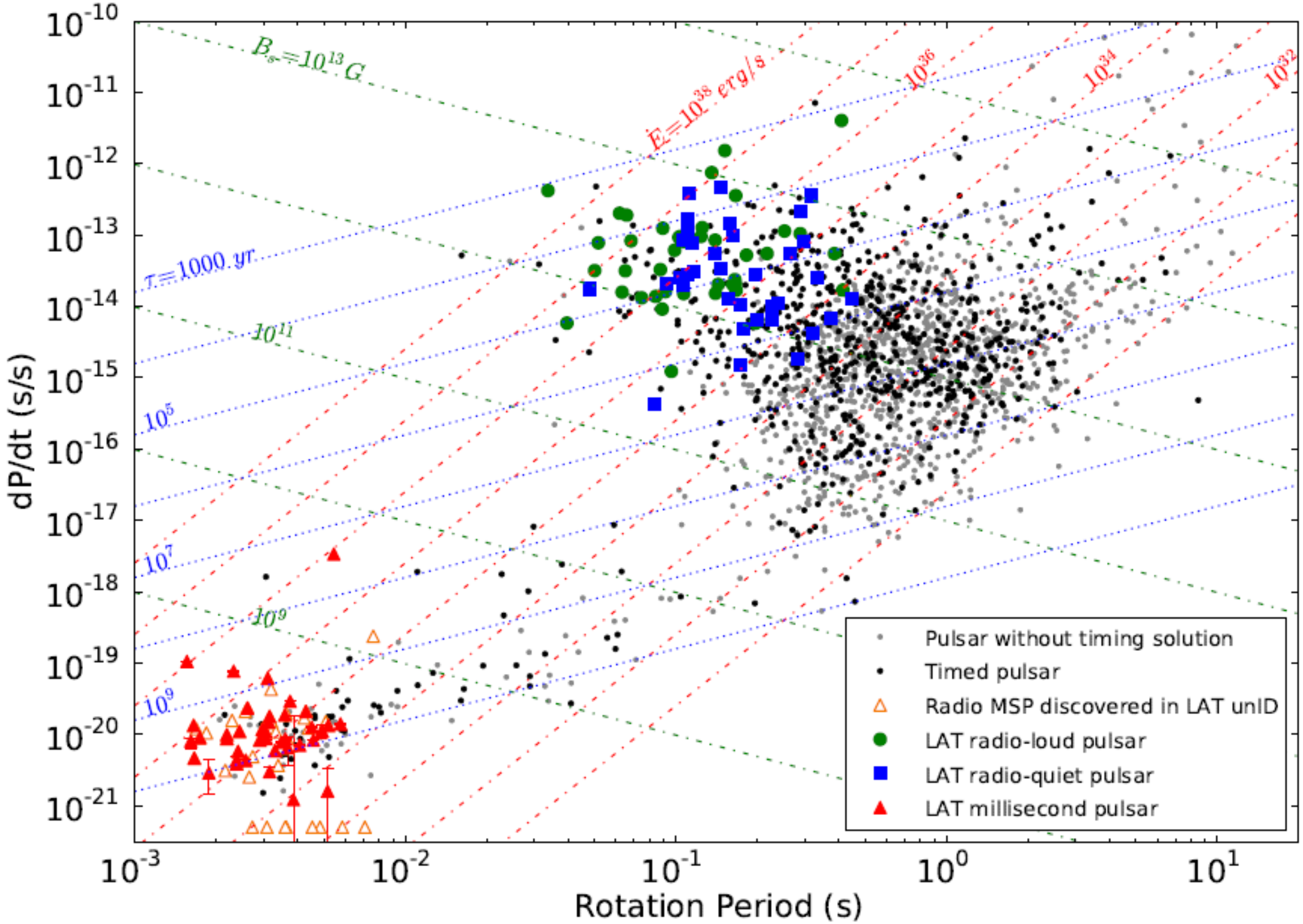


PULSARS



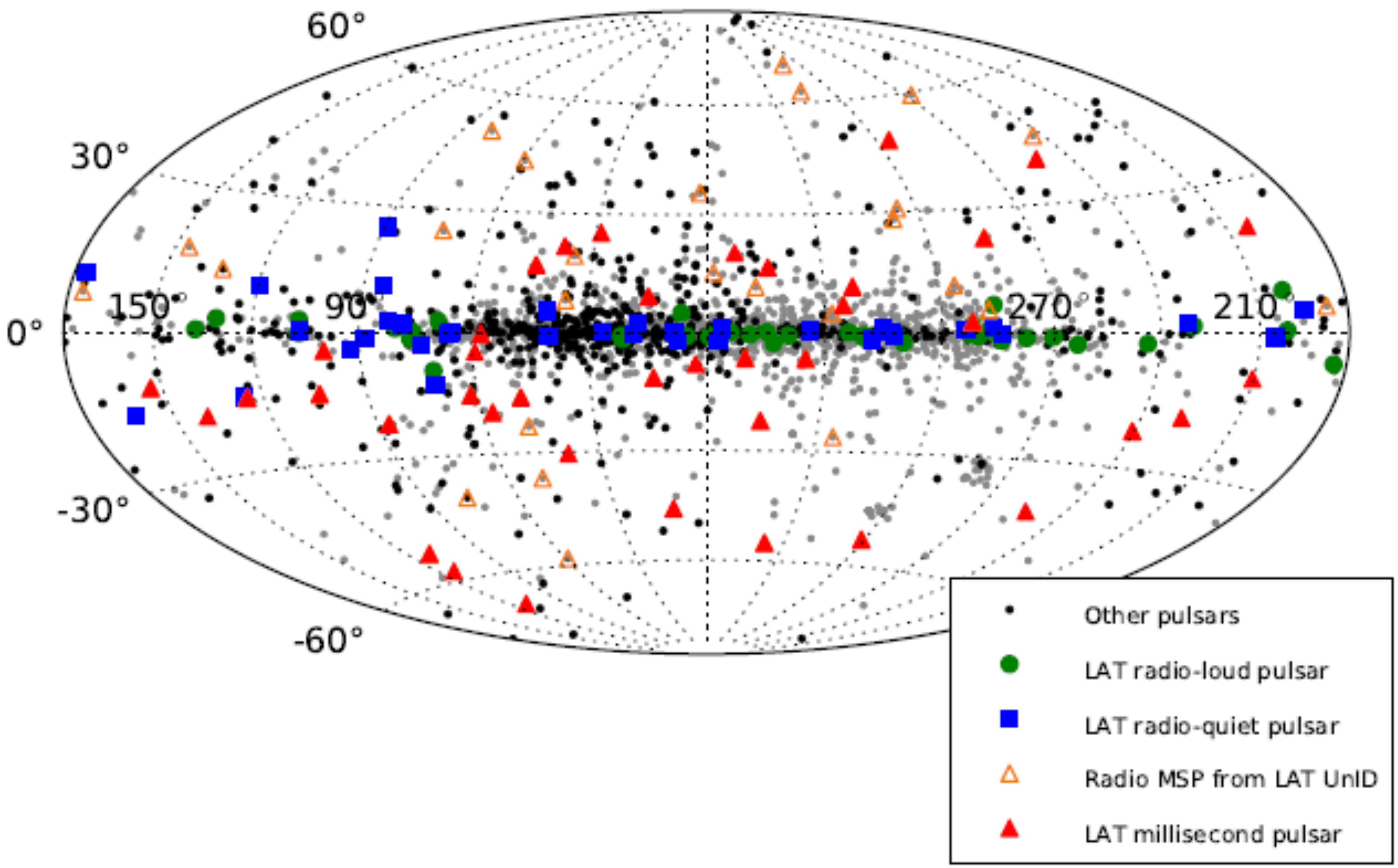
b=+90°
l=+180°
l=−180°
b=−90°
High−energy pulsars
Millisecond pulsars
Radio pulsars

PULSARS



$B_s=10^{13}G$
$\dot{E}=10^{38}\ erg/s$
10^{36}
10^{34}
10^{32}
$\tau=1000\ yr$
10^{11}
10^{5}
10^{7}
10^{9}
10^{9}
dP/dt (s/s)
Rotation Period (s)
Pulsar without timing solution
Timed pulsar
Radio MSP discovered in LAT unID
LAT radio-loud pulsar
LAT radio-quiet pulsar
LAT millisecond pulsar

PULSARS



60°
30°
0°
-30°
-60°
150°
90°
270°
210°
Other pulsars
LAT radio-loud pulsar
LAT radio-quiet pulsar
Radio MSP from LAT UnID
LAT millisecond pulsar

PULSARS

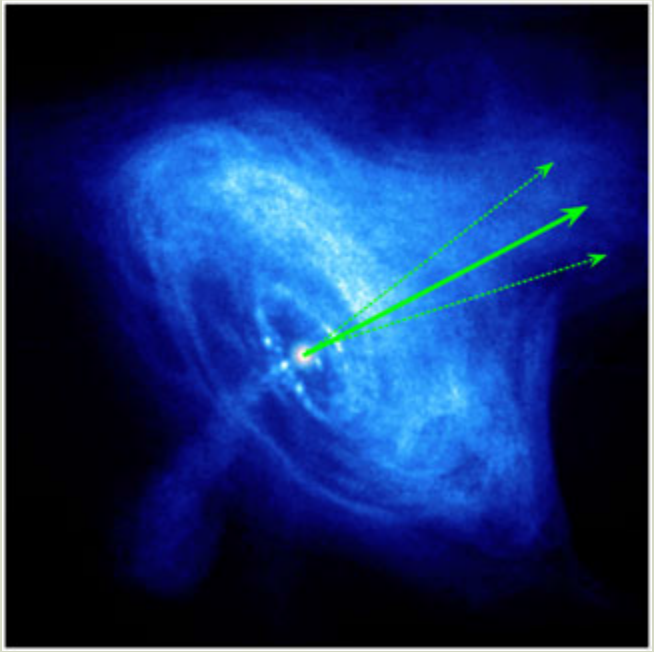
- In 1932, Sir James Chadwick discovered neutron
- In 1934, Walter Baade and Fritz Zwicky proposed neutron stars could be formed in supernova explosions of massive stars
- Pulsars should be born near their parents, which is massive stars and confined to the Galactic plane
- However, James Gunn and Jeremiah Ostriker of Princeton University found that the pulsar distribution extends much further from the Galactic plane
- If $\tau = 10^{5} - 10^{8}\ yr$, and extend $\sim 500\ pc$ from Galactic plane, they must have traveled speed of $\sim 150\ km\ s^{-1}$ to get to that height
- This is nearly $10^{48}\ erg$ of kinetic energy for each pulsar - $0.1 - 1\%$ of the supernova explosion energy itself that created each runaway object

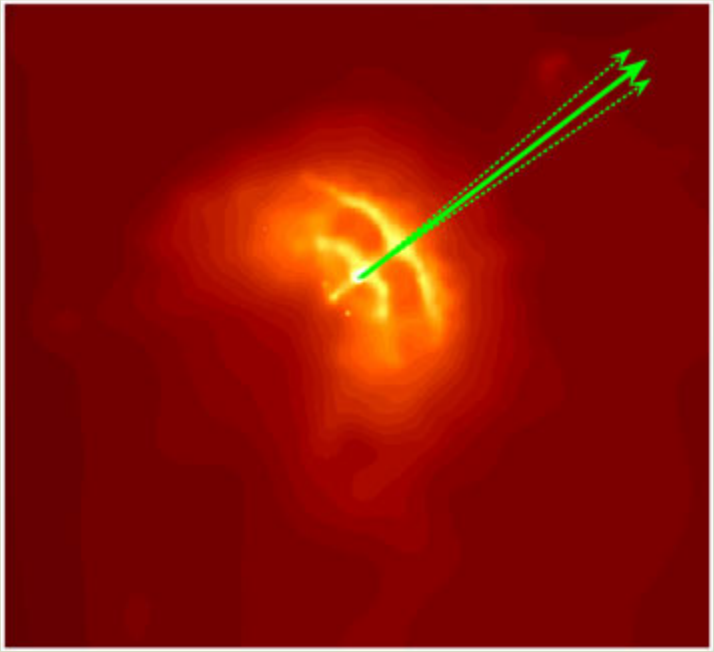
PULSARS

- Few key pulsars are confirmed to be moving away from the Galactic plane
- Many pulsars should be born in supernovae and given a “kick” that propels them away from the Galactic plane
- After traveling only $\sim 500\ pc$ from their origin, the pulsars die and become a non-radio-emitting neutron stars, orbiting the Galaxy repeatedly but not pulsating

PULSARS

- In 1999, after launching the Chandra X-ray observatory, an important property was discovered, pulsars produced jet, like black holes
- Both the Crab pulsar and Vela supernova remnant have oppositely-directed, twin jets appear to be moving at $100-150$ $km\ s^{-1}$ along the same direction as their jet are pointing





PULSARS

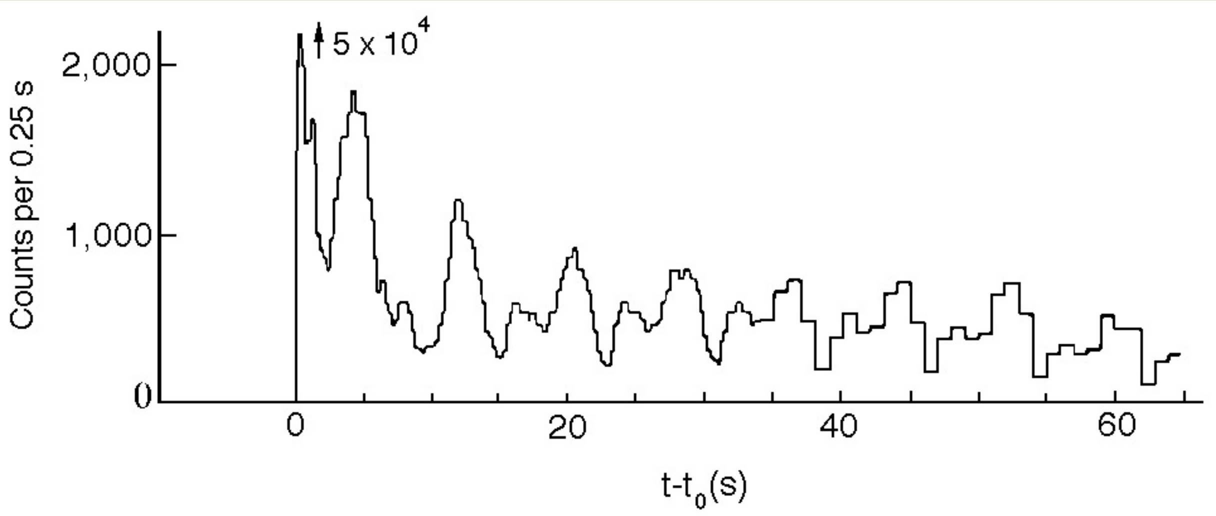
- One of the jets may be stronger than the other, providing a net thrust to each pulsar, acts like a cosmic rocket engine
- However, the present Crab Pulsar's jets have not produced enough momentum, which is only 1% of the required momentum
- There was a much stronger jet propelling the pulsar from Galactic plane during supernovae

MAGNETARS

- Extremely magnetic neutron stars ($\sim 10^{15}\ G$, several order greater than typical pulsars)
- One millisecond is about as short of a period as has been measured for a pulsar
- If we take $1\ ms$ as the shortest typical pulsar period possible
- Time for the period to be doubled is $3\tau = 25\ min$
- In a thousand years, it would have a spin period of 8 seconds and would not produce any pulsar dipole radio radiation

MAGNETARS

- It was first proposed by Christopher Thompson, now at the Canadian Institute for Theoretical Astrophysics in Toronto, and Robert Duncan, now at The University of Texas at Austin to explain the “soft γ-ray repeater” or SGR
- The pulse period are $5-8\ s$, and the spindown rate are of order $\dot{P} \sim 10^{-10}$, which have led to SGRs are magnetars with field of $2-4\times 10^{14}\ G$ and age of only a fer thousand years

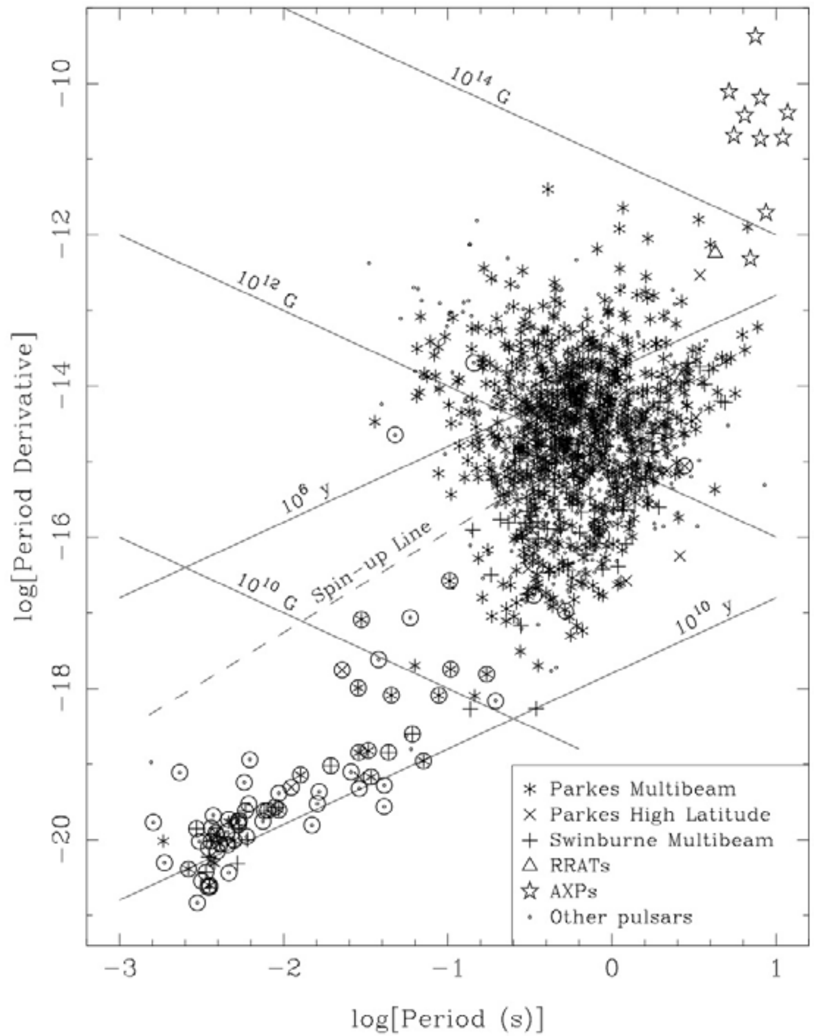


MAGNETARS

- The second type of magnetars is the “anomalous X-ray pulsar” or AXP
- Pulsate in X-ray with periods of around six seconds
- Not in binary system
- Emit much more energy than they should given their slow rotation
- It was proposed to be a magnetar breaking down its enormous magnetic field to produce those extra energy
- One of the AXPs was discovered to be an SGR, which confirm the hypothesis for AXPs
- However, what causes a magnetar to sometimes be an SGR is still not known

MAGNETARS

- AXPs are shown in the upper right region of the figure
- Most of the these object are only a few thousand years old and have a magnetic field of $10^{14} - 10^{15}\ G$



MAGNETARS

- The third type of magnetars is probably X-ray Dim Isolated Neutron star or XDIN
- Weaker in X-ray luminosity than the AXPs
- Weaker field and older than AXPs $(2-3\times 10\uparrow 13\ \ G,\ 1-2\ Myr)$
- Both of XDIN and AXP are a factor of ten more magnetized than normal pulsars
- Although only few of them are found, it is believed to be a very large population of strong field neutron stars - as many as there are normal radio pulsars since they are so close together

RRATS

- RRATs (Rotating Radio Transients)
- Short radio bursts of $2–30\ ms$ duration separated by time intervals ranging from 4 minutes to 3 hours
- Each RRAT is visible in the radio for only one second per day
- But still we can measure the period for ten of the eleven RRATs and spindown rate for three of them
- Two of them have normal magnetic field ($\sim 10 \uparrow 12\ \ G$) and age ($2-3\ Myr$)
- The remaining one has a ten-times stronger magnetic field and is only a hundred thousand years old
- Half of the sources have similar period to the AXPs

RRATS

- Again, the explanation of the phenomenon is still not clear
- One may propose that RRATs and XDINs are the same population of objects
- With RRATs at larger distance than XDINs so that X-ray is not detected
- And we have not yet been able to detect the short radio bursts in XDINs yet because we simply have not tried hard enough yet, or because the pulsar fan beam does not intersect the earth

GEMINGA AND OTHER NEARBY NEUTRON STARS

- If pulsars live for a few million years, and the rate of production in the Galaxy is about equal to the supernova rate
- $\sim 10^5$ pulsars are in our Galaxy
- There must be at least one active radio pulsar only $200-300$ pc away if they are evenly distributed
- The discovery of Geminga at distance of 157 pc away from us indicate that the closest active radio pulsar may be found, either Geminga or one of the XDINs
- If counting the dead one, there should be one in 40 pc and there must be $200-300$ pulsars in the distance of the Geminga

NEUTRON STAR X-RAY BINARIES

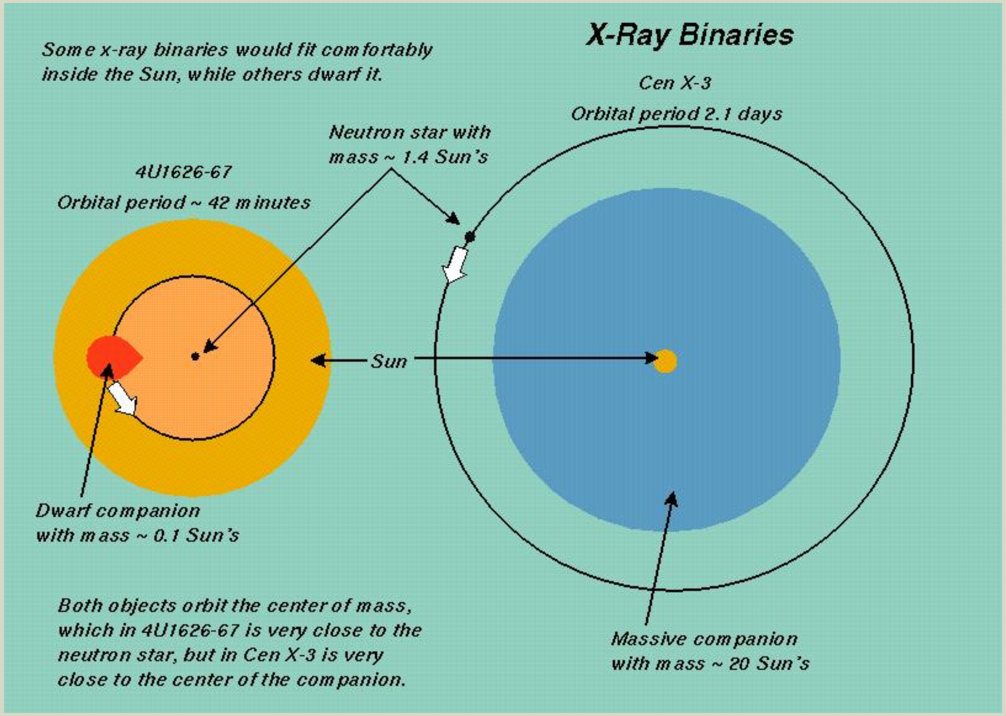
- It is important to the study of true black hole because they behave similarly in accretion and jet-producing properties
- But neutron stars can grow considerably in mass when merging with a companion neutron star
- When it reaches the critical mass of $2.5-3.0\ M\downarrow\odot$, it will collapse to black hole

NEUTRON STAR X-RAY BINARIES

- In 1967, Iosif Shklovskii, of the Sternberg Astronomical Institute in Moscow, suggested that Sco X-1 could be a neutron star powered byaccretion of matter from a binary companion
- However, the short duration of the sounding rocket observations prevented identification of any periodic variations in the X-rays
- In December 1970, the Uhuru satellite was launched
- By 1972 it was known that sources such as Centaurus X-3 and Hercules X-1 were periodically eclipsed *and* that they also pulsed in X-rays every few seconds
- The pulsations were speeding up over time

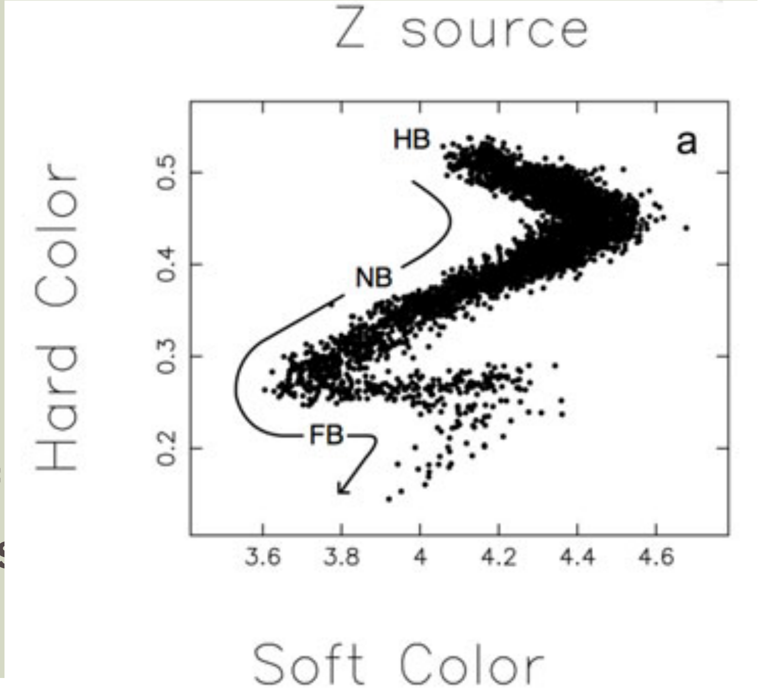
NEUTRON STAR X-RAY BINARIES

- These observation have led to three conclusion
- Accretion from a companion indeed was occurring and probably was responsible for producing the X-rays
- The X-ray star was probably a magnetized neutron star
- The accreting matter was probably orbiting that neutron star in a disk spinning up the X-ray pulsations as the disk's orbital motion pushed onto the pulsar's magnetic field



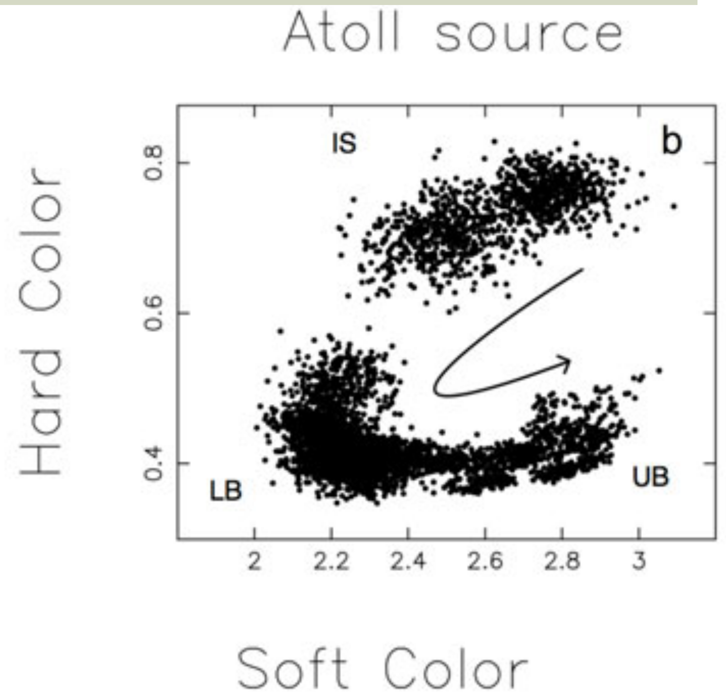
NEUTRON STAR X-RAY BINARIES

- Some neutron star X-ray sources have spectra similar to Cen X-3 or Her X-1 have been classified according to how their X-ray emission behaves when one compares high-energy and low-energy X-ray colors at different times in their evolution
- A “Z” source produces a zigzag pattern in the color–color diagram
- These changes are believed to be produced by variations in the accretion rate, and therefore the luminosity
- Z sources have magnetic fields of 10^{10} G and are accreting near the Eddington limit of $\sim 10^{18}$ $g\ s^{-1}$ f their ~ 1.5 $M_{\odot}$ neutron star masses



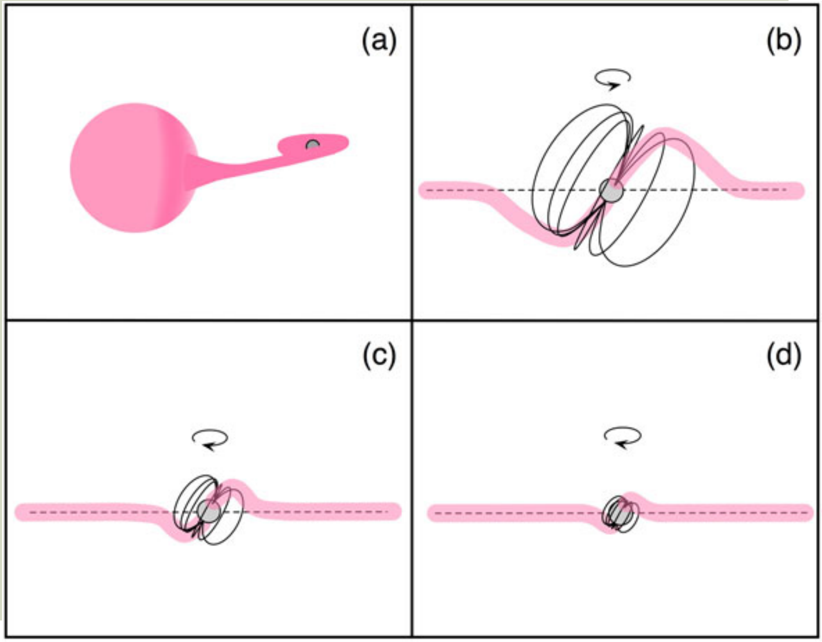
NEUTRON STAR X-RAY BINARIES

- An "atoll" source produces island-shaped and/or boomerang-shaped patterns in the color–color diagram
- It is appear to be accreting much more slowly in only a few percent Eddington
- look like the NB/FB part of a Z source diagram
- The absolute luminosity of an atoll is much lower than that of a Z source
- Michiel van der Klis has suggested that atoll sources have even weaker magnetic fields ($\sim 10\uparrow 8 \quad G$)
- In 2002, Rob Fender showed that the Z and atoll sources both produce jets apparently in a manner similar to the isolated pulsars and not unlike the powerful radio galaxies and quasars



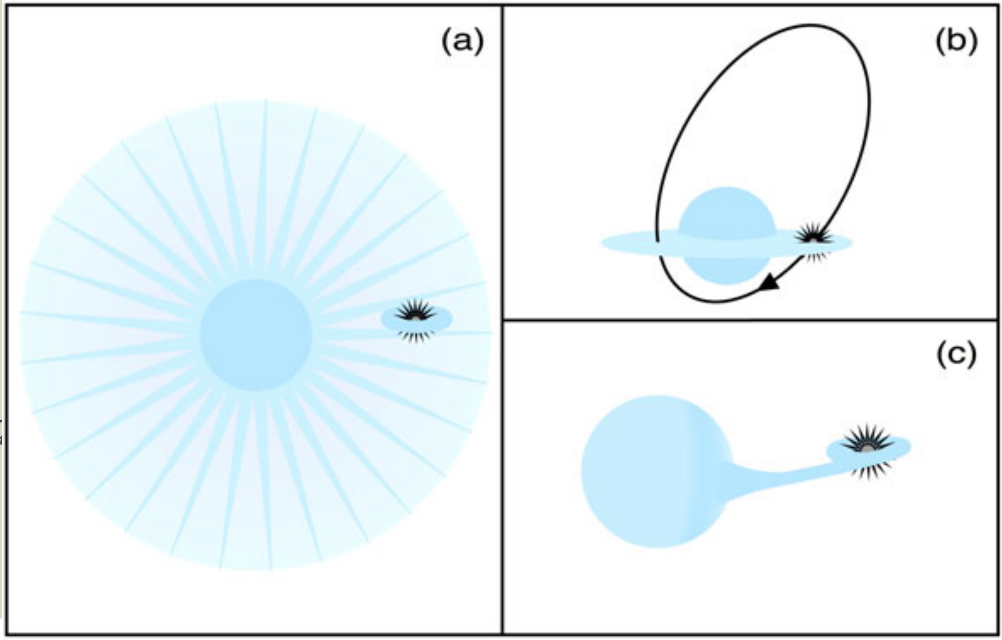
NEUTRON STAR X-RAY BINARIES

- There are more than 300 binary X-ray sources known and is divided into 4 classes: whether the X-rays are persistent or transient and whether the binary companion is a low-mass or high-mass star
- LMXBs typically have a K or M dwarf companion or sometimes another type of low-mass star that is $<1\ M_{\odot}$
- HMXBs typically have an O or B star companion, $10-20\ M_{\odot}$ in mass
- In the LMXB case it is due exclusively to "Roche lobe overflow"
- All the Z sources and atoll sources are LMXBs
- Accreting material must reach the neutron star surface at the polar region, creating hot spots at the pole



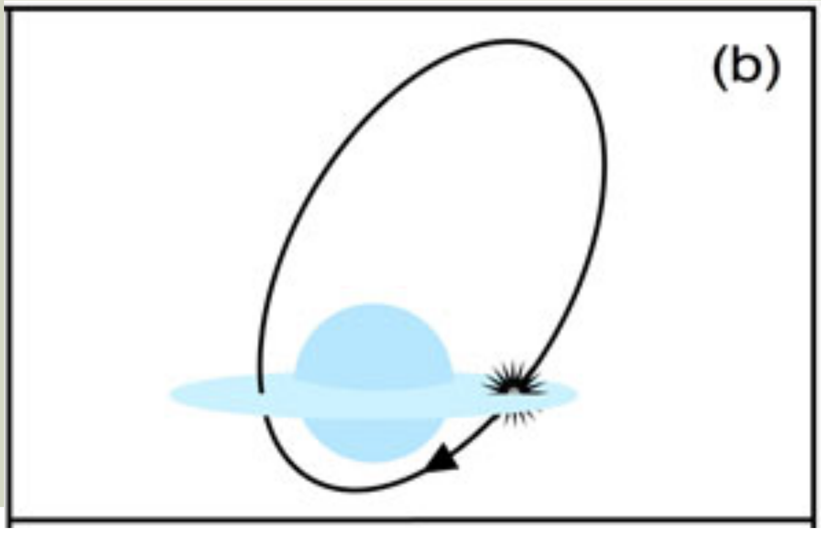
NEUTRON STAR X-RAY BINARIES

- In the HMXB case, there are two other methods of mass transfer
- Accretion of part of a powerful stellar wind emitted by the O/B star
- Accretion from an equatorial disk of gas surrounding a companion star when the orbiting neutron star crashes temporarily into that disk
- Roche lobe overflow of the high-mass star also is possible, but this generally tends to produce enormous accretion rates of $10^{19-22}\ g\ s^{-1} >> M_{Ed}$



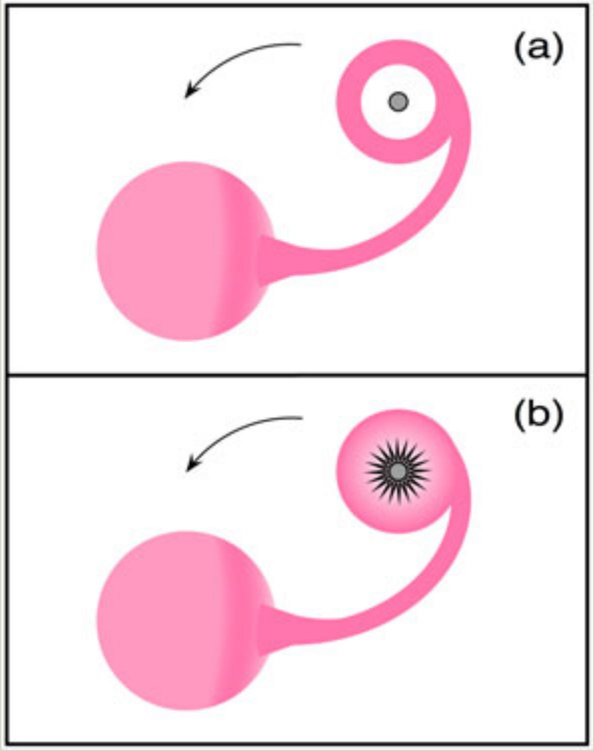
NEUTRON STAR X-RAY BINARIES

- Both LMXBs and HMXBs can be "persistent" or "transient" sources. Transient sources are not merely variable
- They appear bright in X-rays for a short time (a few days or weeks) and then disappear
- Some transients return years later, some still have not come back after erupting decades ago
- In the high-mass case the X-rays can be transient when the X-ray star is in an elliptical orbit



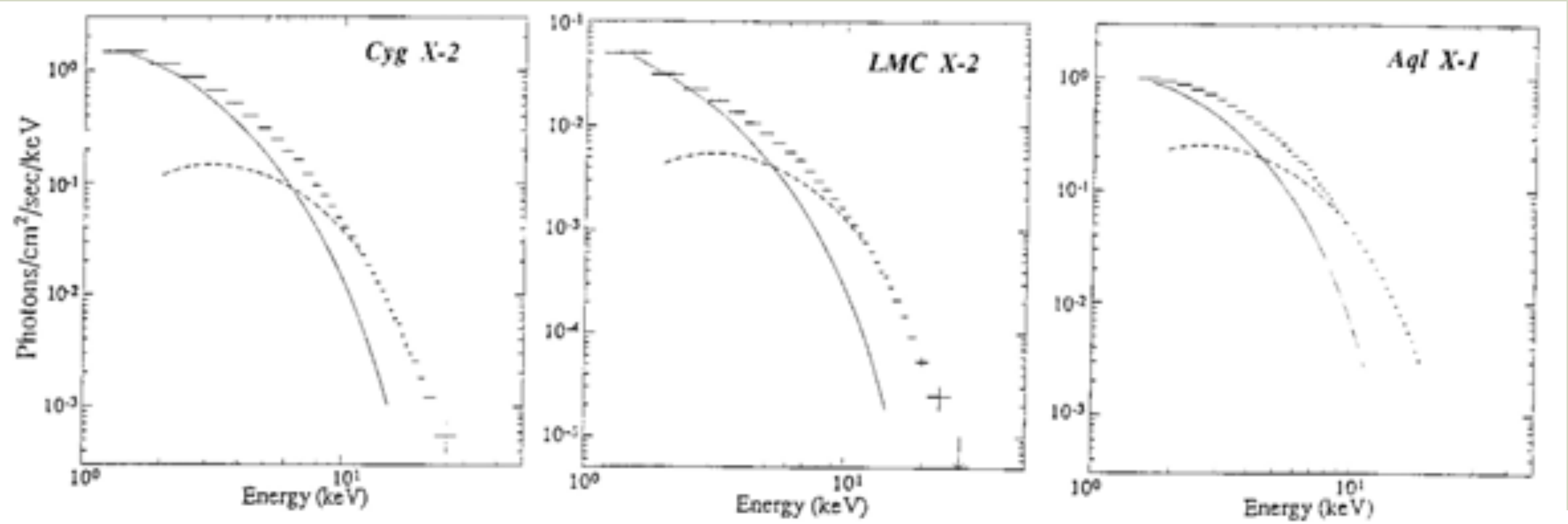
NEUTRON STAR X-RAY BINARIES

- Suggested by Jean-Marie Hameury, Andrew King, and Jean Pierre Lasota
- For accretion rates below about 1016 g s−1, the accretion disk around the X-ray source does not accrete steadily
- Matter from the Roche lobe overflow collects in a ring far from the X-ray star
- At some point that ring becomes dense enough to be turbulent and then accretes rapidly onto the neutron star, but only briefly as the ring is quickly emptied
- The explosion is also relatively cool



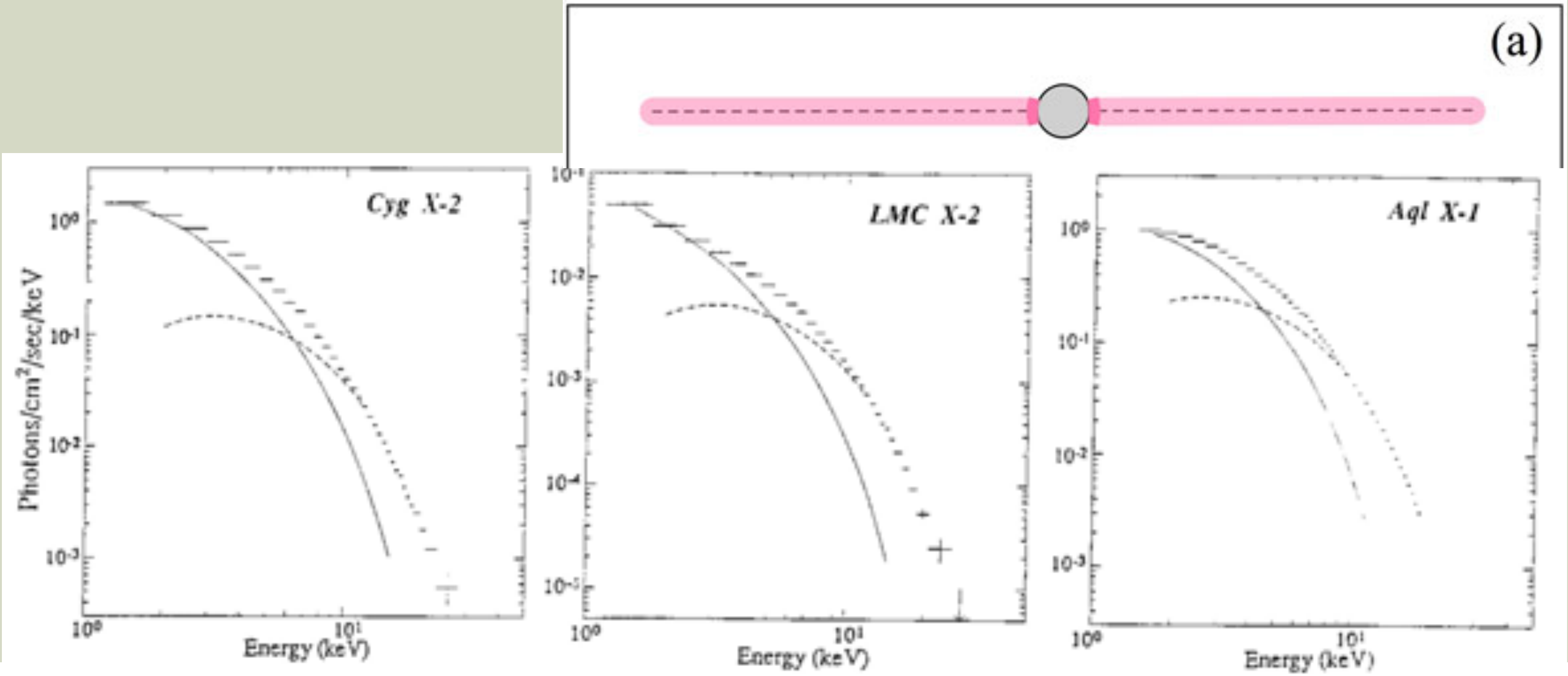
NEUTRON STAR X-RAY BINARIES

- The X-ray spectrum of a neutron star accreting near the Eddington limit makes it easy to tell that the X-ray star is not a true black hole
- It is made up of two thermal components
- The first is a soft, multi-temperature spectrum that one expects from accretion disks (solid line)
- The hottest temperature in the disk is about $1.5\ keV$ or $17\ MK$



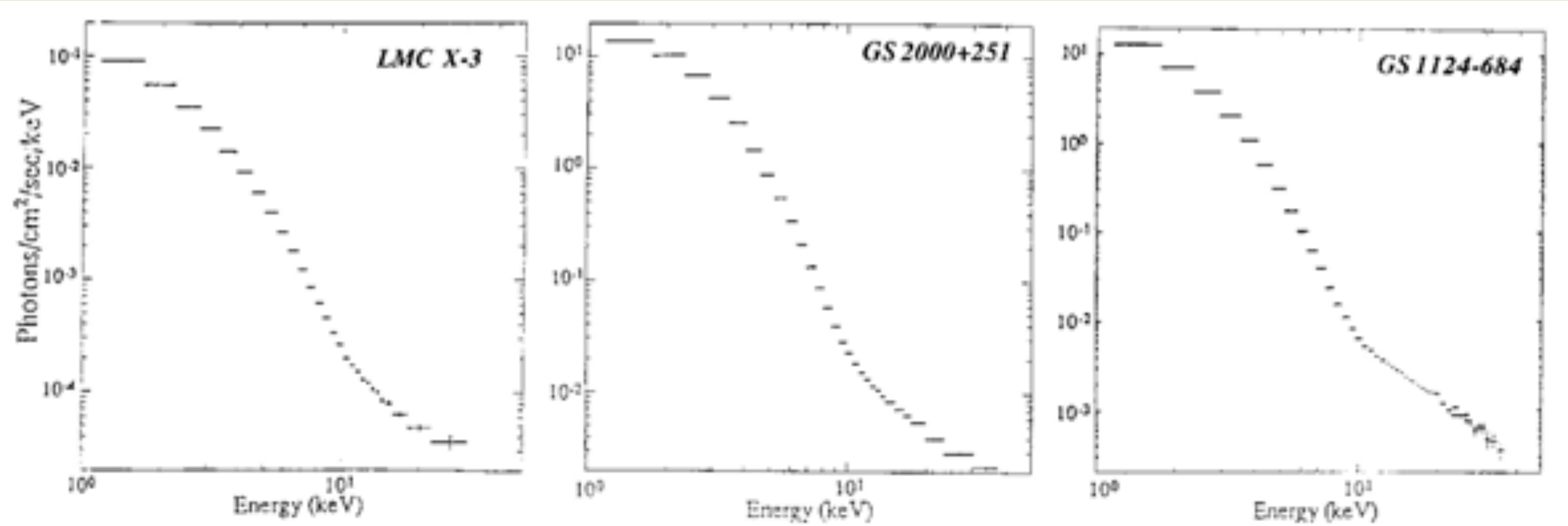
NEUTRON STAR X-RAY BINARIES

- There is an even hotter component, about $2.4\ keV$ or $28\ MK$, that is produced when the accreting plasma strikes the neutron star surface (dotted line)
- This hotter thermal component is considered to be the signature of an accreting hard-surfaced neutron star



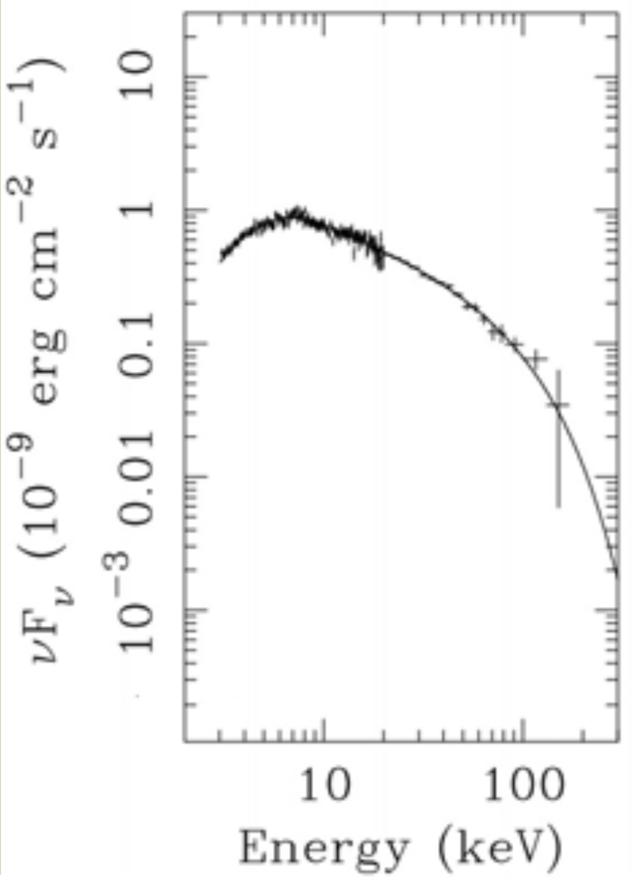
NEUTRON STAR X-RAY BINARIES

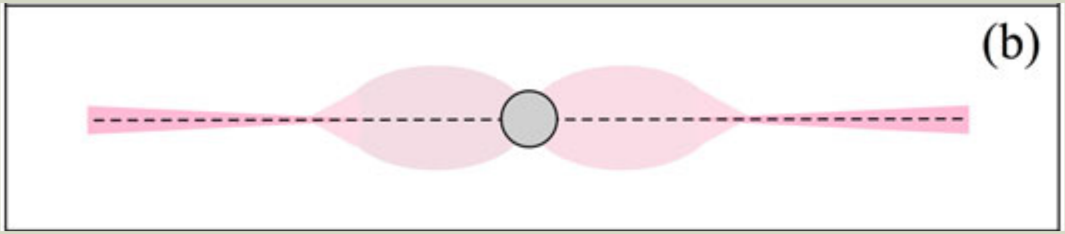
- Black holes do not have this hotter thermal X-ray spectral component
- The black hole spectra also have a hard, power-law component above $10\ keV$
- However, the Z sources also show similar hard power-law tails extending beyond $10\ keV$



NEUTRON STAR X-RAY BINARIES

- The accretion disk X-ray spectrum described above is usually referred to as the "high/soft state" whenever the accretion luminosity in the X-ray binary exceeds about $10^{37}\ erg\ s^{-1}$
- As the accretion rate drops, the spectrum changes to a simple power law ($f_\nu \propto \nu^\alpha$), with $\alpha = -0.5$ to -1.0 and a cut-off at very high temperatures approaching $100\ keV$
- This hard component is believed to be produced by Compton scattering of cool photons by hot electrons in an optically thin corona or inner bloated torus
- This accretion state is called the "low/hard state"
- The accretion rate that is well below 10% of the Eddington limit





NEUTRON STAR X-RAY BINARIES

- In addition to the random noise in the disk, there appear to be oscillatory, almost periodic, variations in the X-ray flux as well
- These “quasi-periodic oscillations”, or QPOs, tend to be of two kinds
- A slow variation near a frequency of one oscillation every few seconds
- A very rapid variation near $1000\ Hz$
- QPOs give clues to the structure of the accretion disk
- First, the kHz QPO may be related to pulsar, but the pulsation is much less stable than the classic millisecond pulsar
- Second, a more likely hypothesis is that the kHz HF QPO is associated with the Keplerian orbital frequency at a distance of less than twice the neutron star’s radius of about 10 km

NEUTRON STAR X-RAY BINARIES

- It has been proposed that the difference between the two oscillations is indeed the pulsar frequency
- The difference is of order $200–300\ Hz$ which is reasonable for a pulsar being spun up by accretion
- This beat frequency difference often tends to decrease when the QPOs get faster for some reason but it remains stable at times in some sources
- There is currently no model that can explain all of these and other properties of kHz QPOs in neutron star X-ray binaries

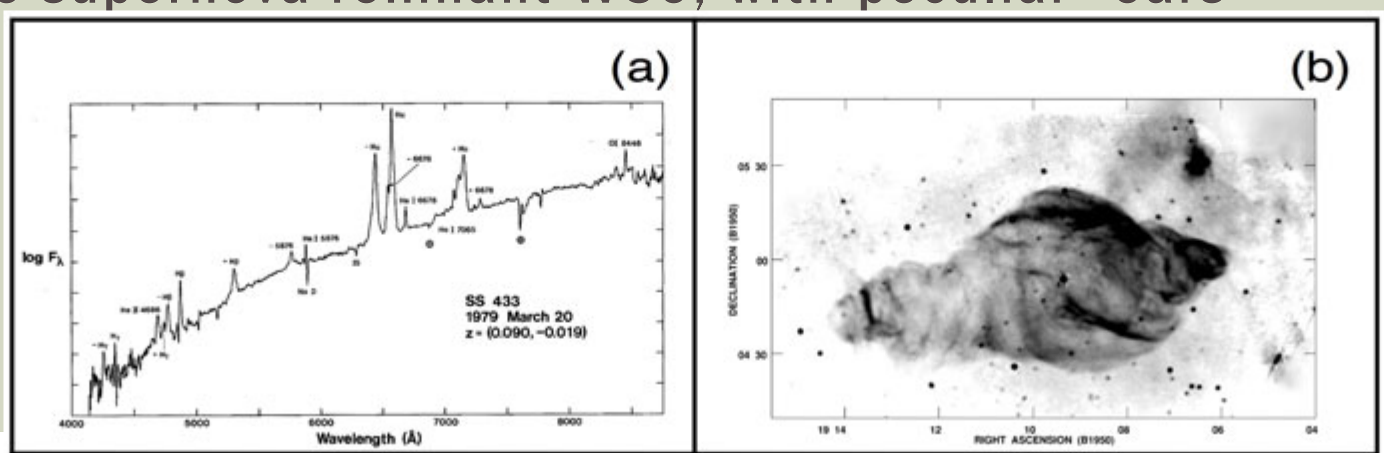
NEUTRON STAR X-RAY BINARIES

- The low-frequency QPOs occur in Z and atoll sources when they are in low/hard state
- These oscillations also are a mystery
- If related to Keplerian rotation, the oribital distance is $100–200\ km$
- LF QPOs occur simultaneous with the faster variety
- Sources with more rapid kHz QPOs also have more rapid LF QPOs
- QPOs should be depending on the process of disk accretion
- Another important piece of the puzzle is that radio emission from an X-ray binary and the “C-type” LF QPOs often occur together
- Suggest that at least some LF QPOs occur in the accretion disks and are directly related to the acceleration of a radio jet
- may be an important clue to how accretion disks make jets

THE STRANGE CASE OF SS433

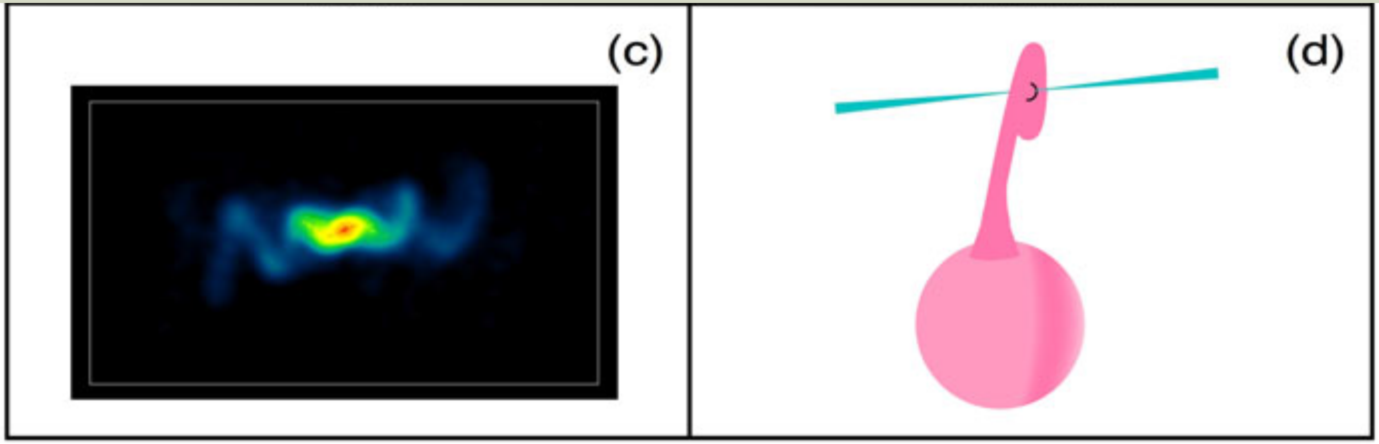
- In 1979 Bruce Margon and his colleagues announced the discovery of a remarkable object SS433
- Hydrogen emission lines are at enormous positive and negative velocities of order one-quarter the speed of light
- these emission lines moved back and forth in the spectrum by many thousands of kilometers per second, with a sinusoidal period of about 164 days

- Radio observations showed that around the source lay the large supernova remnant W50, with peculiar "ears"



THE STRANGE CASE OF SS433

- Inside that remnant was a “corkscrew” jet-like flow that changed on the same time scale as the emission lines did
- While this energetic source was weak in X-rays
- The most likely explanation for the source is a neutron star or black hole is accreting from a companion at a rate much greater than the Eddington limit, creating a temporary star-like envelope around the compact object and hiding from our view the X-rays that are produced by that accretion
- Also, the spinning compact object that produces the jets and the accretion disk must have different rotation axis so that the jet precess with a 164-day period



THE STRANGE CASE OF SS433

- Objects like SS433 are extremely rare because the lifetime is only of order $10^{5-6}\ yr$ which is several hundred times shorter than that of a normal X-ray binary
- We should expect to find one SS433 compared to the several hundred X-ray binaries now known
- Because the X-ray is hidden from our view, it is not sure if it is a black hole or a neutron star

RECYCLED PULSARS

- In 1982 Donald Backer and his colleagues announced the discovery of a pulsar with a period of $1.5\ ms$ - PSR 1937+21
- This period is close to the rotation rate at which the spinning neutron star becomes unstable and the rotation speed at its equator is $0.1c$
- However, measurement of its spindown rate indicated an old object ($\tau \sim 2\times 10^{8}\ yr$) with a magnetic field of only $4\times 10^{8}\ G$ and $\dot{P} \sim 10^{-19}$
- The pulsar was spun up by accretion in an X-ray binary system
- However, PSR 1937+21 has no evidence of a binary companion larger than a very small planet

RECYCLED PULSARS

- The “millisecond pulsar” remained somewhat of a mystery until the late 1980s and early 1990s when a new class of fast binary pulsars was discovered
- The new pulsars are not strong X-ray sources, but they are very fast radio pulsars with magnetic fields of only $\sim 10^8$ G
- Their companions are other neutron stars or white dwarfs, so accretion onto the pulsar from its companion is minimal at the present time
- This binary system have to survive two supernovae explosion

RECYCLED PULSARS

- The accretion played an important role in the past
- These are close binary systems in which mass transfer could have taken place
- The pulsars with the fastest spin periods also have the weakest magnetic fields
- Accretion spun up the pulsar, but also destroy the magnetic field
- There are some binary radio pulsars with companion stars so low in mass that they could not have formed by any astrophysical means other than being slowly consumed by the accreting pulsar
- A few more isolated millisecond pulsars have been discovered showing that their companion stars were consumed entirely

BINARY PULSARS

- So far, only one of each binaries is detected as a pulsar because the other is dead or its fan beam does not sweep the earth
- These binary pulsar systems are rich physics laboratories for testing general relativity
- The first binary pulsar was discovered by Hulse and Taylor in 1974
- The two neutron stars are orbiting each other with a high eccentricity
- The closest approach is only $1.1\ R_{\odot}$ so that the gravitational interaction is so strong
- Their orbital period was decreasing at a rate of $76\ \mu s\ yr^{-1}$, which is predicted by general relativity precisely, show that there is gravitational wave radiating in the cosmos

FORMATION OF NEUTRON STARS

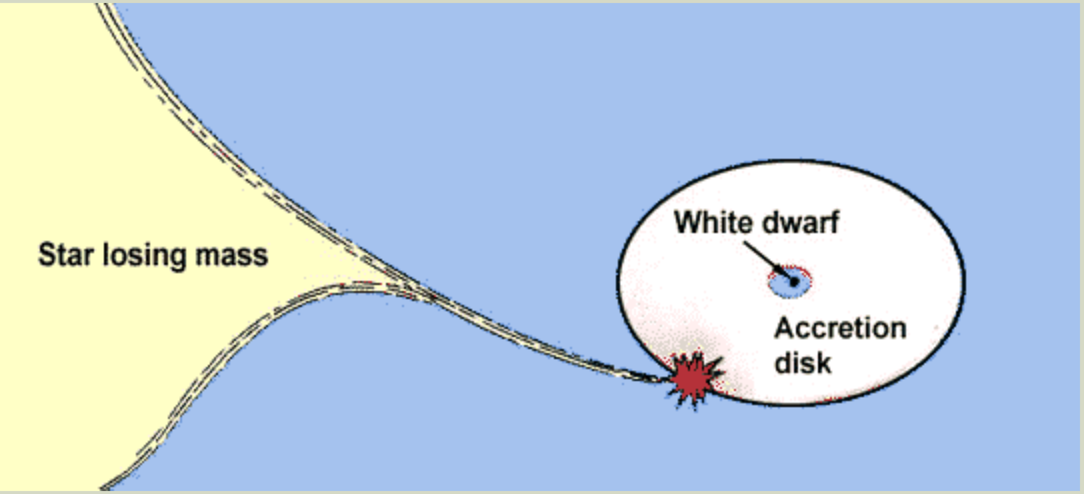
- Come from supernovae
- Type I – no hydrogen detected in the explosion
  - Type Ia: iron lines detected at late times (6 months after the explosion)
  - Type Ib: some helium also detected; oxygen and calcium detected at late times
  - Type Ic: no helium detected; oxygen and calcium detected at late times
- Type II – hydrogen detected in the explosion
  - Type IIP: "plateau" light curves: the supernova brightness remains at the same value for 1–3 months after the explosion
  - Type IIL: "linear" light curves: the supernova brightness decreases linearly with time after the explosion begins
  - Type IIn: "nebular" spectra: narrow emission line cores inside broad emission line wings (like a Seyfert spectrum)
  - Type IIb: similar to Type Ib, but weak hydrogen lines detected

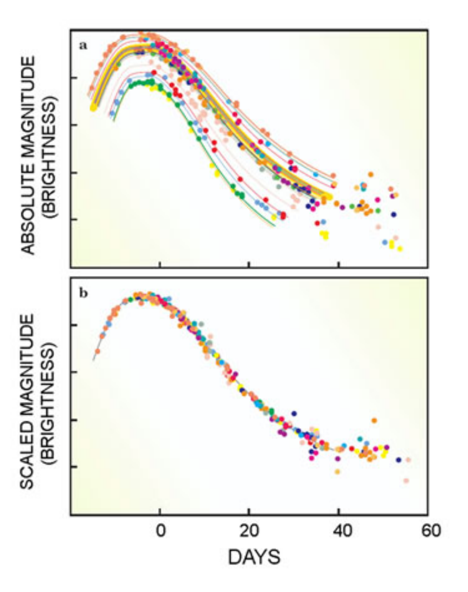
SUPERNOVAE

- Only Type Ia supernovae is detected in most type of galaxy
- The other types occur only in late type galaxies and only in or near regions of recent star formation
- All supernovae except Type Ia must come from massive stars with short lifetimes that have recently formed only in the last few million years
- However, the precise manner in which most supernovae explode is still controversial

TYPE IA SUPERNOVAE

- Occur in white drawf stars with carbon–oxygen cores
- Triggered by accretion from a low-mass companion that recently expanded to fill its Roche lobe and dumping matter onto the white drawf
- The white drawf “explode” when its mass exceeds $\sim 1.4\ M\downarrow\odot$
- The light curve are similar as the origins are the same
- However, there is no neutron star remnant





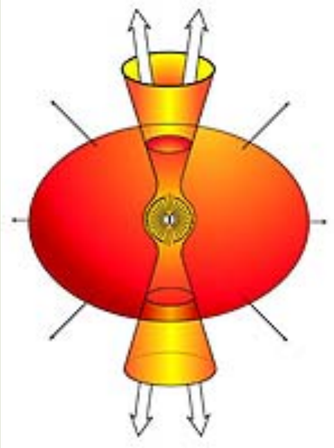
OTHER SUPERNOVAE

- “iron core collapse” supernovae similar to the Crab explosion
- Hydrogen -> Helium -> Carbon -> Oxygen -> Silicon -> Iron
- When the core reaches the Chandrasekhar critical mass of $\sim 1.4\ M_{\odot}$, it collapses to a hot proto-neutron-star
- It cools by neutrino emission to a degenerate neutron star about 10 km in radius
- It releases $\sim 5\times 10^{53}\ erg$ of binding energy, much of which goes into neutrinos and other forms of emission
- Only $\sim 10^{50-51}\ erg$ is tapped to eject the stellar envelope and cause the supernova explosion that we detect
- The mechanism is still unclear but it is clear that we see different types of core collapse supernovae simply because they occur in different types of envelope

OTHER SUPERNOVAE

Supernova type	Envelope type and size	Observed polarization	Inferred elongation
II	**Hydrogen;** $10^{13}\ cm$	1%	$2:1$
IIb	**Helium;** $10^{12}\ cm$	2%	$2.5:1$
Ib/c	**Oxygen;** $10^{11}\ cm$	$3-5\%$	$>3:1$

- A recent work is done by Lifan Wang of The University of Texas at Austin and his colleagues
- Light becomes polarized when the object that is being viewed is not symmetric
- The explosion is elongated like a cigar, not spherical



OTHER SUPERNOVAE

- The degree of polarization increases as the size of the envelope around the exploding core decreases
- Core-collapse supernova explosions are highly asymmetric in the interior and powered by a jet that is produced in the collapse
- If the explosion occurs in a very large envelope, the jet action is absorbed by that envelope, resulting in a fairly spherical explosion
- However, with most of the envelope gone, the jet action has a more visible effect, resulting in a highly-elongated explosion

TYPE IC-BL SUPERNOVAE

- Only a few are currently known
- Characterized by expansion velocities that are significantly above the typical $0.02c$ speeds of normal supernovae
- Also characterized by the ejection of large amounts of iron peak elements, particularly radioactive nickel, which is formed in the explosion and then decays to iron in a few months

ISOLATED STELLAR-MASS BLACK HOLES

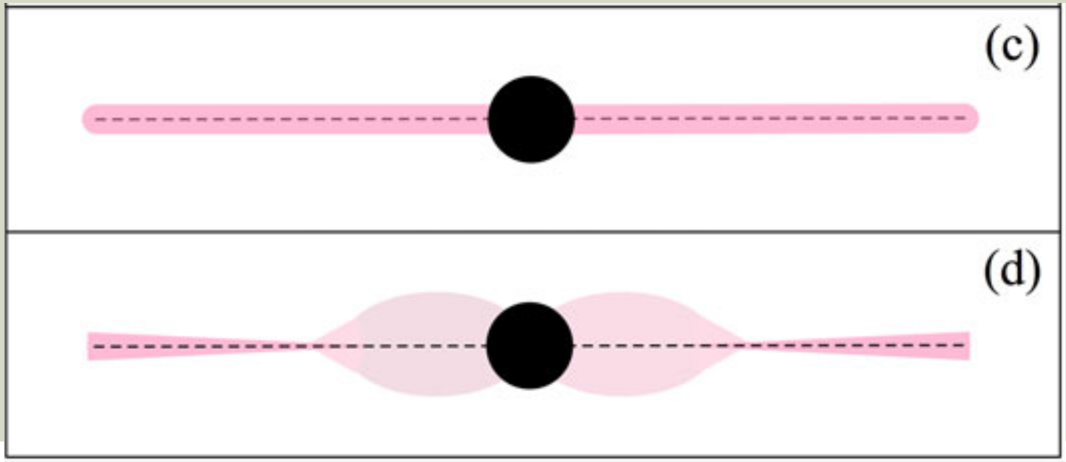
- Black hole power some of the brightest and most powerful engines in the universe
- However, when the black hole is isolated, it is truly black and emit no detectable light. Finding it is difficult
- In 1999, two group, the MAssive Compact Halo Objects (MACHO) project and the Optical Gravitational Lensing Experiment (OGLE), started monitoring tens of millions of stars in the Magellanic clouds and Galactic center bulge
- They have discovered the object OGLE-1999-BUL-32 and MACHO-99-BLG-22
- In 2002, the two group performed gravitational microlensing obeservations which lastd for 641 days, yielding a long enough time base for a good parallax effect to be detected, yielding a long enough time base for a good parallax effect to be detected, giving a lens mass of $37\ M{\downarrow}\odot$, although with considerable uncertainty

ISOLATED STELLAR-MASS BLACK HOLES

- The MACHO team found two more objects 96-BLG-5 ($3–16\ M_{\odot}$ in mass) and 98-BLG-6 ($3–13\ M_{\odot}$)
- Because of the large mass and no detectable emission, it is possible that these objects are black hole of several solar mass
- If so, then a considerable fraction of the Galaxy’s mass, perhaps as high as 1%(?), might be locked up in one hundred million isolated stellar-mass black holes (SBHs)
- However, the rate derived here is about a factor of 4 greater than that derived below, so perhaps only one of these three microlensing events may be real

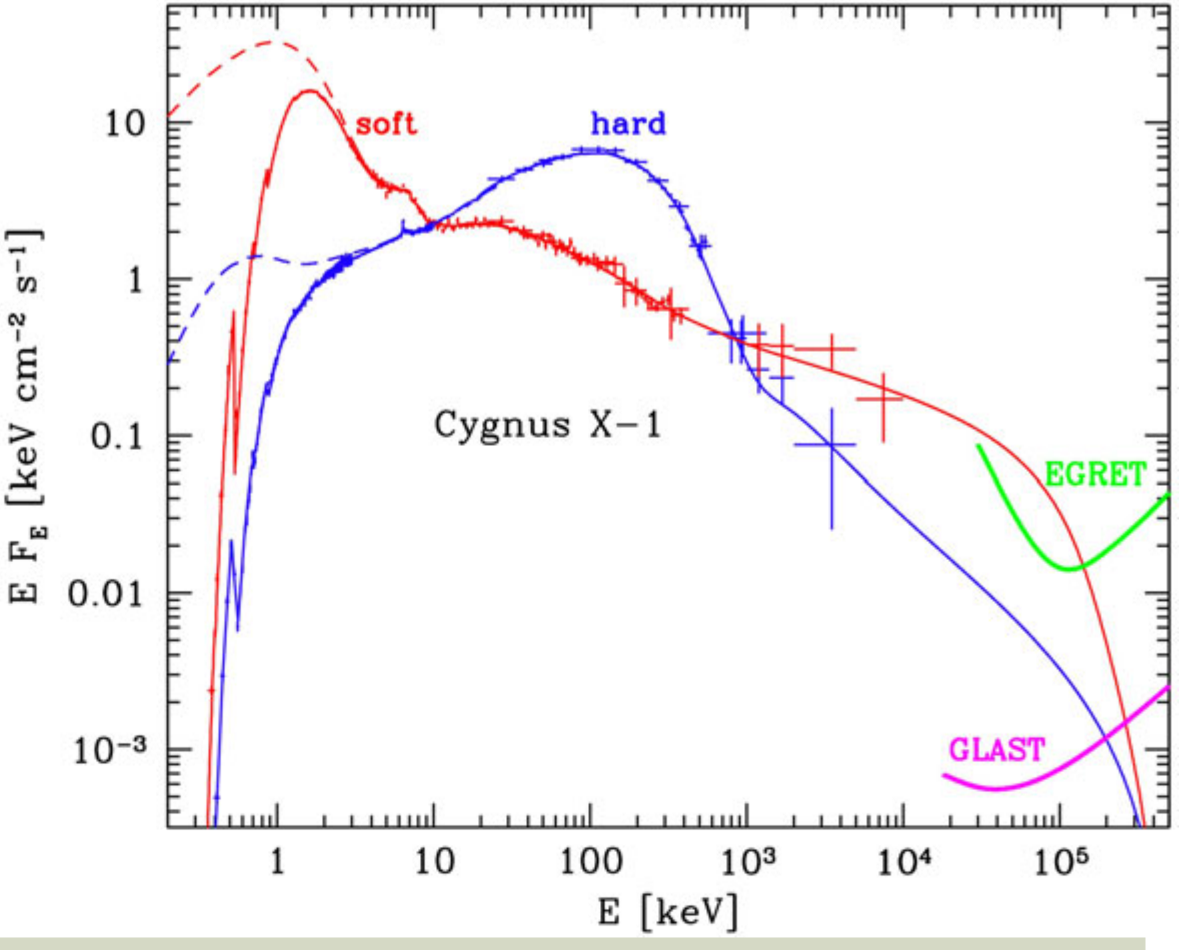
BLACK HOLE X-RAY BINARIES

- Other than the mass measurement of the X-ray sources, another major black hole indicator is the spectrum
- As talked before, the spectrum of black hole X-ray binaries is rather soft as black do not have a hard surface
- The state is said to be high/soft when the accretion rate is well above $\sim 10^{17}\ g\ s^{-1}$
- Like neutron star X-ray binaries, the one without torus is high/soft state and the other is low/hard state as the radiation emitted by the cool disk is scatter up in the torus and result in a harder spectrum



BLACK HOLE X-RAY BINARIES

- When the accretion rate is well below $\sim 10^{17}\ g\ s^{-1}$, it shows a softer spectrum
- When the accretion rate is well above $\sim 10^{17}\ g\ s^{-1}$, it shows a harder spectrum
- The peak shift from $\sim MK$ to $\sim GK$, which show that the disk is being heated in low/hard state



BLACK HOLE X-RAY BINARIES

- By observing a variety of black hole binaries, other accretion states have been identified although the exact set of states and their characteristics are still under investigation
- First, the intermediate state lies between the low/hard and high/soft states
- Distinguished mainly by the types of QPOs produced in this state
- Second, the very high, unstable state, occurs when the accretion rate approaches the Eddington limit
- The disk undergoes dramatic changes in character, cycling through the three state in a matter of minutes

BLACK HOLE X-RAY BINARIES

- Some observers prefer to identify each individual structure through which the disk passes as a separate state
- However, except VHS state, the other state are accretion rate based, and VHS has accretion rate near Eddington
- So we choose the state to be the accretion rate based
- While the structure based state are called sub-state

BLACK HOLE X-RAY BINARIES

- QPOs also occur in black hole X-ray sources as it is in neutron star binaries
- QPO in black hole system are come into LF and HF, and the period of the two types of QPOs appears to be correlated from source to source
- While there is still some differences from the neutron star system
- These differences can be accounted for the mass different mass
- As the time scale is proportional to the mass, the definition of LF and HF for neutron star system and black hole system are offed by a factor of 10, i.e., $10\ Hz$ and $1\ kHz$ for neutron star while $1\ Hz$ and $100\ Hz$ for black hole

BLACK HOLE X-RAY BINARIES

- There are QPO doublets in neutron star system while it does not exist in black hole system
- The absence of doublet in black hole system indicates the QPO doublets may be due to the beating of the spinning neutron star magnetic field with a single high-frequency QPO producing in the orbiting disk
- Also, the LF QPO and HF QPO do not occur simultaneously, with LF QPO occur in low/hard state and HF QPO occur in VHS
- It is due to the difference in Keplerian frequency, because the inner radius is large in hard state and small in soft state
- However, why the accretion returns to exactly the same very high state, with the same high-frequency QPO, is still not understood

BLACK HOLE X-RAY BINARIES

- Like neutron star X-ray binaries, black hole binaries can be divided into four classes: LMXB or HMXB, and, persistent or transient
- However, the distribution is different from neutron star binaries
- HMXB are rare, and persistent one are very rare.
- It appears that HMXB make black hole binaries less often than neutron star binaries because black hole are made less often and the formation of black hole is violent that may unbind the binaries

a. Neutron star X-ray binaries (85%)

X-ray binary mass class	Persistent	Transient
HMXB	23%	21%
LMXB	~27%	~14%

b. Black hole X-ray binaries (15%)

X-ray binary mass class	Persistent	Transient
HMXB	1.5%	<1%
LMXB	<1%	12%

BLACK HOLE X-RAY BINARIES

- Similarly, there are very few low-mass binary black hole systems with persistent X-ray emission
- One of the famous persistent LMXB is the "Galactic Center Source" 1E 1740.7-2942, discovered by the Einstein X-ray satellite
- Radio images made by Felix Mirabel and Luis Rodriguez show a double-lobed structure very similar to that of radio quasars
- These authors coined the term "microquasar" for the source
- Majority of black hole X-ray binary systems known are the LMXB transients - the black hole X-ray novae
- The black hole X-ray novae last only a short period of time, therefore, it can explain why most black hole binary systems were not discovered with sounding rockets as the flights last only a few minutes and so have little chance of catching a transient X-ray nova explosion

CLASSICAL MICROQUASARS

- Microquasars are identical miniature copies of the macroquasars
- Have the same feature of macroquasars
- Producing thermal heat emission in their accretion disks and producing jets
- The jets propagate in nearly the speed of light and produce miniature radio lobes
- Superluminal motion may occur
- 1E 1740.7-2942 is the first microquasar discovered
- Looks very similar to a typical double-lobed quasar
- It is only 7 kpc distant and its lobes extend only 2 pc

CLASSICAL MICROQUASARS

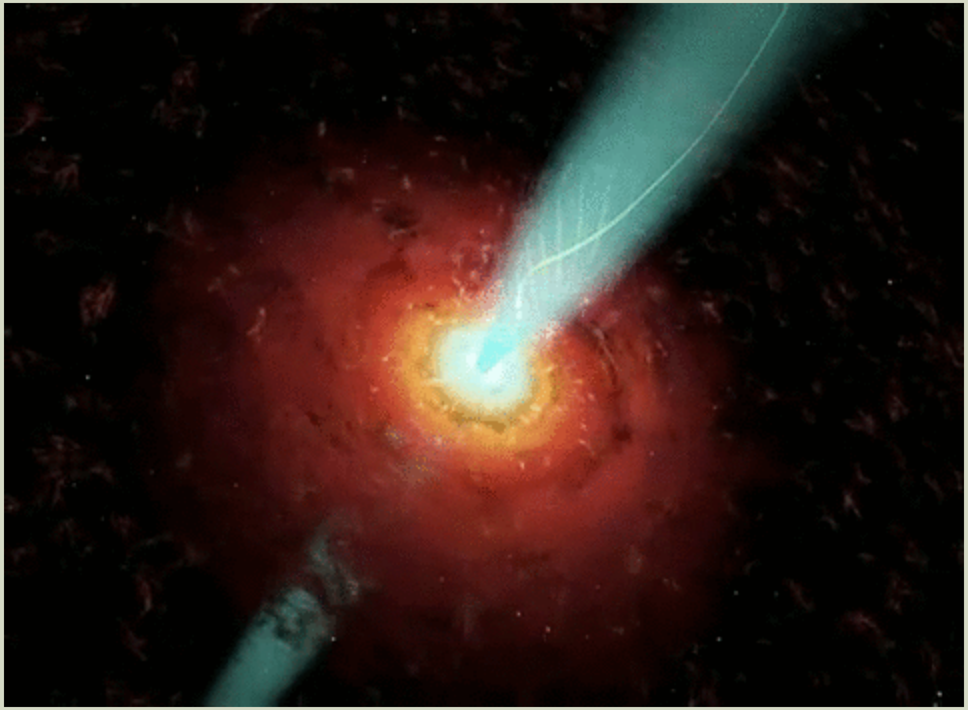
- In mid 1992, a team led by Alberto Castro-Tirado used the Russian Space Research Institute's γ-ray satellite GRANAT to discover what would turn out to be the missing link between micro- and macroquasars: GRANAT Source 1915+105
- It has passed through essentially all the accretion states exhibited by other binary X-ray sources
- When it is in a very high-luminosity state, it can cycle through numerous accretion sub-states in minutes or hours
- At a distance of $12.5\ kpc$ ($40000\ ly$), its luminosity reaches or exceeds $10^{39}\ erg\ s^{-1}$, which means it is at least $10\ M_{\odot}$
- It also produce jet which apparently pointed at an angle of about $30°$ and travelling at a Lorentz factor somewhere between 2.5 and 5, similar to quasar jet speed

CLASSICAL MICROQUASARS

- When it is in hard state, it produce a steady, weak jet, similar to 1E 1740.7-2942, supermassive black hole at the center of our Galaxy and LLAGN
- In 1996, Jochen Greiner, Edward Morgan and Ronald Remillard used the newly-launched Rossi X-ray Timing Explorer to discover a large variety of timedependent oscillations in GRS 1915+105
- As classified by Tomaso Belloni, there are three separate sub-states that this source cycles through when in its VHS
- Sub-state A, B and C which is similar to soft state, VHS and hard state respectively
- LF QPOs occur in sub-state C only while two HF QPOs occur in sub-state B

CLASSICAL MICROQUASARS

- Also, there can be quick jumps between sub-states in any direction but except from C to B
- Mirabel and his colleagues noticed the link between the X-ray and radio ejections
- At certain times the X-ray emission would “dip” or decrease and shortly thereafter a radio outburst would be detected



CLASSICAL MICROQUASARS

- A similar X-ray dip behavior was later seen in the Seyfert galaxy 3C 120, whose black hole mass is about 3×10^{7} $M_{\odot}$, while GRS 1915+105 has only $10-16$ $M_{\odot}$
- The cycle time is proportional to $M^{0.70}$
- These observations are some of the most important clues to how jets form in quasars of all types
- The ejection of a jet always occurs when the disk is in a hot state

CLASSICAL MICROQUASARS

- GRO J1655-40 was a superluminal radio source
- The radio and hard X-ray emission were correlated
- Lorentz factor similar to that of GRS 1915+105
- Observations with RXTE revealed that there are two high-frequency QPOs, one at 300 Hz and one at 450 Hz
- The faster one oscillates at higher X-ray energies indicating that both QPOs must be related to the Keplerian orbital frequency at two different radii
- For a measured black hole mass of about $6\ M{\downarrow}\odot$, these radii would be about 60 km and 45 km
- While the latter radius is smaller than the standard disk inner radius for a non-rotating black hole
- Indicate that the black hole may be rotating rapidly

CLASSICAL MICROQUASARS

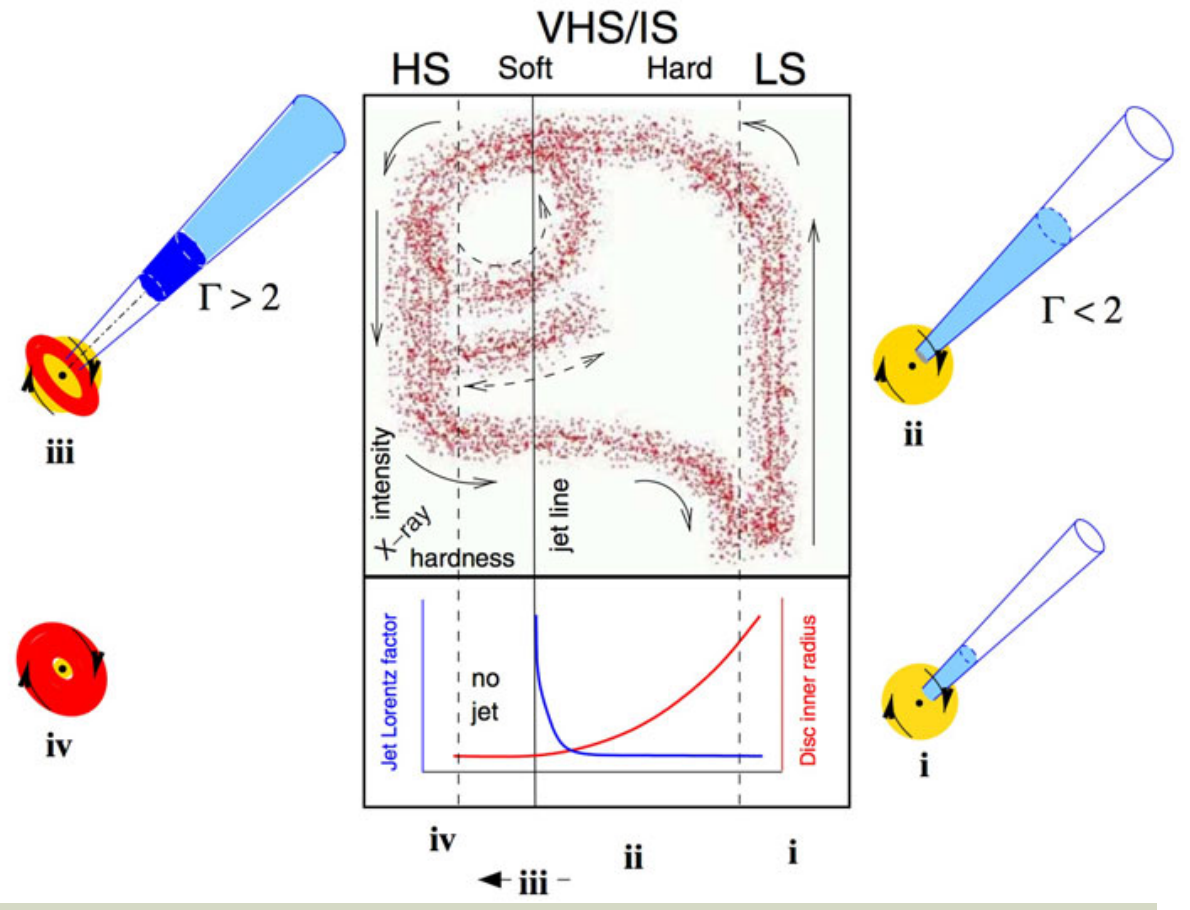
- The predicted radii for the 41.5 and $69\ Hz$ QPOs in GRS 1915+105 are about 300 and $200\ km$, which are significantly *outside* the last stable orbit radius ($125\ km$) for a non-rotating $14\ M_{\odot}$ black hole
- Indicate that the black hole is spinning rapidly in the opposite direction to its accretion disk (Ch 7)

CLASSICAL MICROQUASARS

- There is another X-ray nova with radio jets XTE J1550-564
- It has QPO of 184 and $276\ Hz$
- Similar to GRS 1915+105 and GRO J1655-40, they all have integer QPO ratio
- Włodek Kluzniak suggest that the accretion disks in all three objects were vibrating near their inner edges, with vibrations perpendicular to the disk resonating with vibrations in the radial direction
- Such a model might even explain HF QPOs in the neutron star X-ray binaries better than the current pulsar spin beat model
- However, these models are still not confirmed to be the case

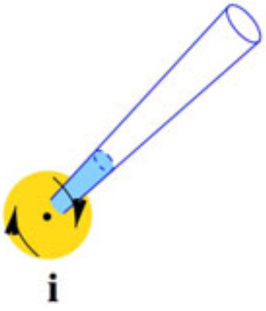
CLASSICAL MICROQUASARS

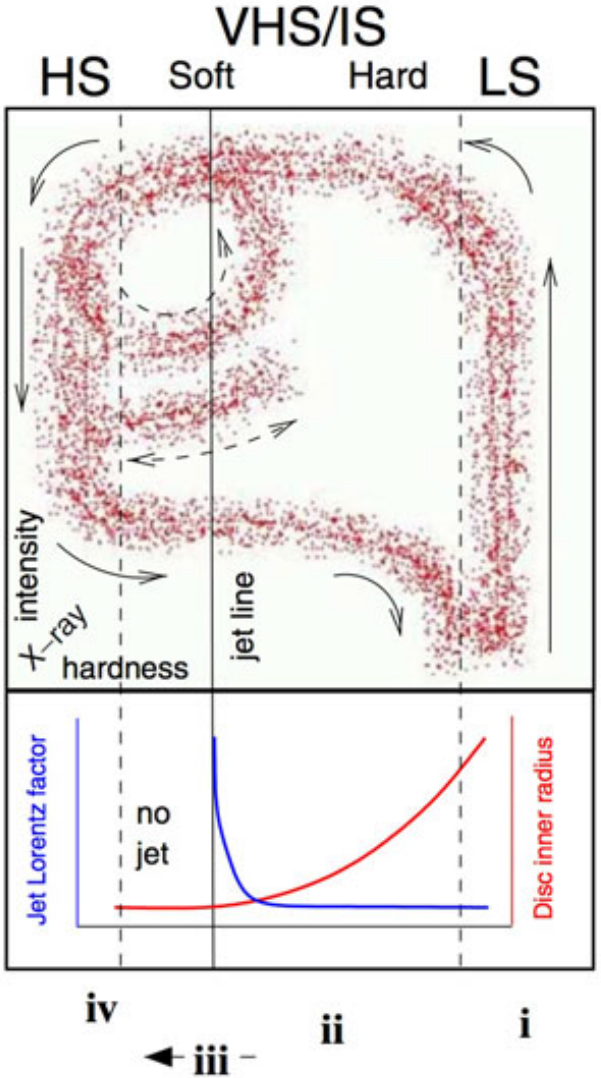
- In 2004 Fender, Belloni, and Elena Gallo collected observations of GRS 1915+105, XTE J1550-564, and two other similar sources, and created a color–magnitude diagram like the HR diagram



CLASSICAL MICROQUASARS

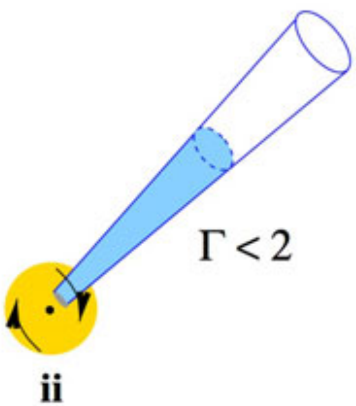
- Region i: Slowly accreting sources at lower right remain hard when their accretion rate increases. While black hole sources produce weak and slow jet
- Have a large torus

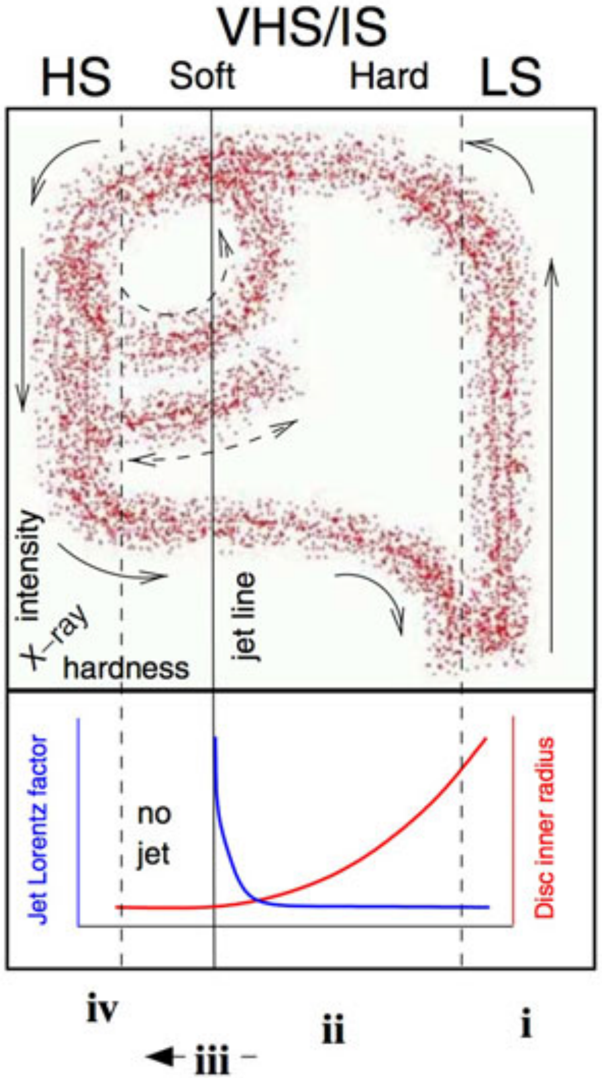




CLASSICAL MICROQUASARS

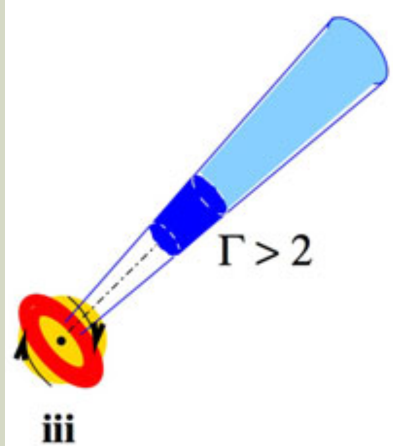
- Region ii: When an rather high X-ray luminosity is reached, the increasingly active source suddenly makes a left turn in the diagram, remaining at about the same apparent intensity in the observed X-ray band, but becoming softer
- This flat evolutionary track is probably due to the limited size of the observing X-ray band, the softer X-ray is absorbed by interstellar medium
- The size of torus is decreasing

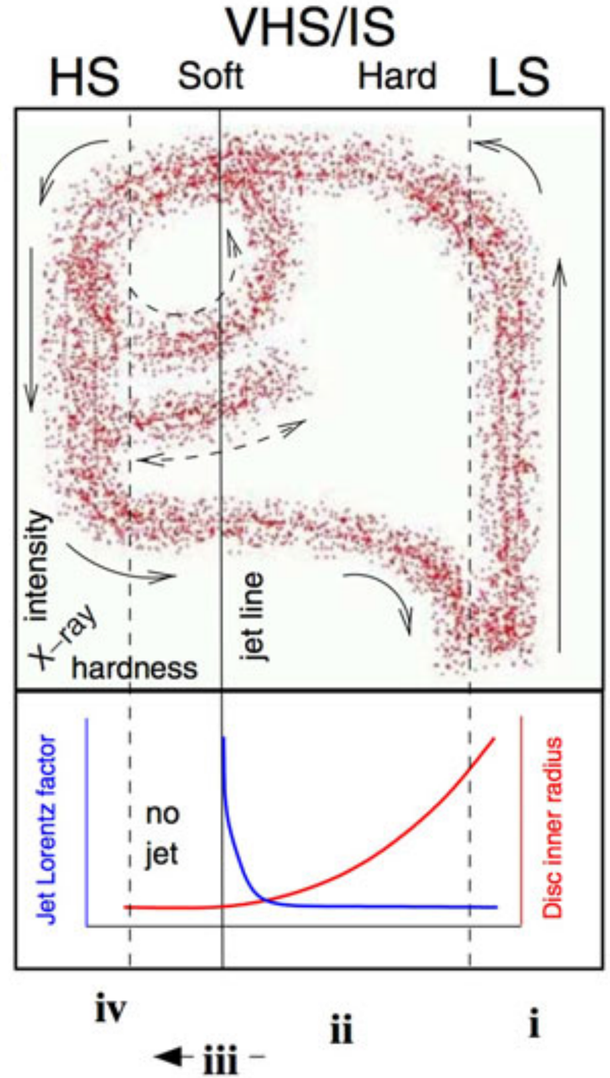




CLASSICAL MICROQUASARS

- Transition iii: High X-ray luminosity produces strong, explosive and fast jet outburst
- The inner portion of disk is emptied

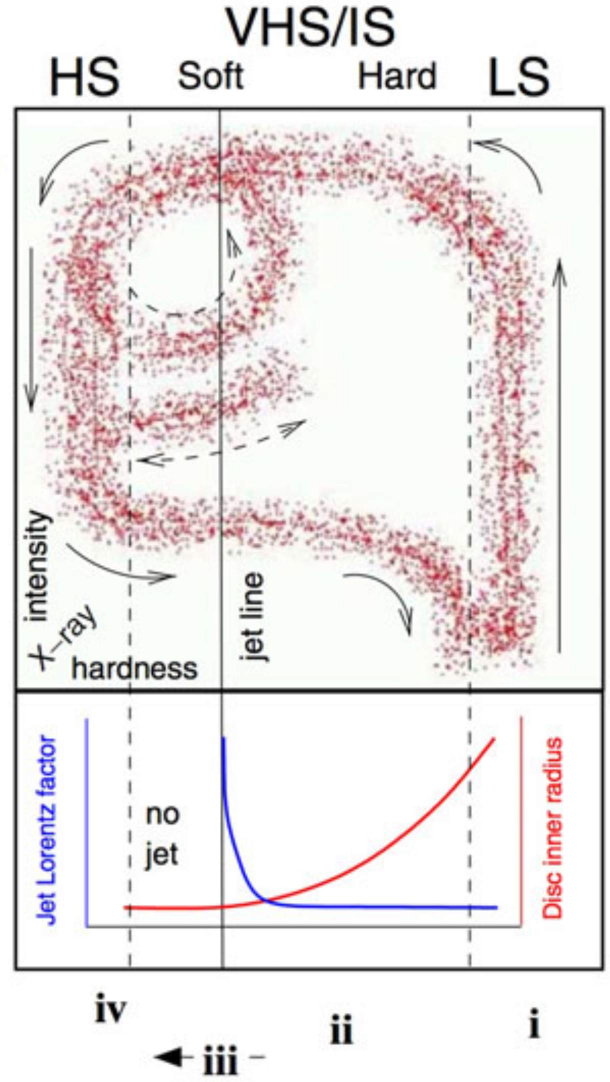




CLASSICAL MICROQUASARS

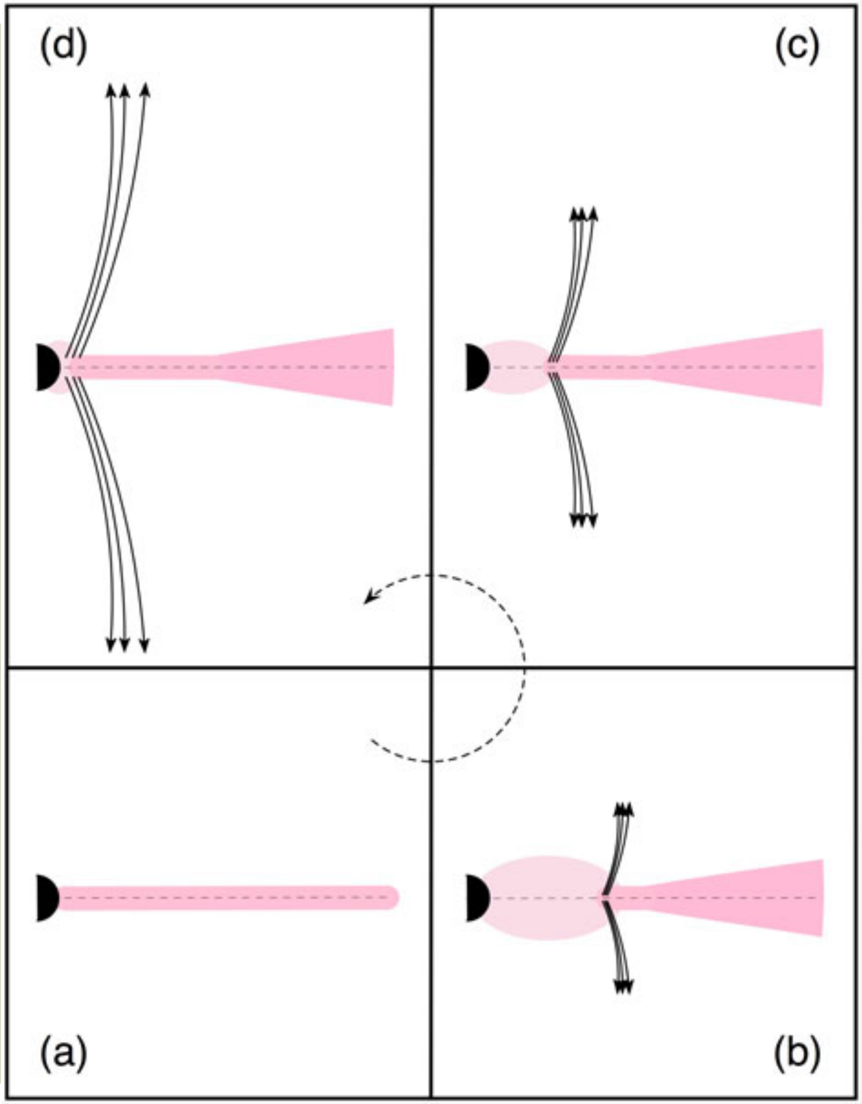
- Region iv: Softward of the jet line the source appears to produce no detectable jet
- A black hole source then maintains a soft spectrum as it decreases in luminosity, makes another sharp turn, this time back toward the low/hard state

iv



CLASSICAL MICROQUASARS

- Starting from (a), the black hole system is in slow accretion rate
- The accretion disk accumulate to from torus
- As the accretion rate increases, the power of jet also increases, while the torus shrink in its size
- Eventually, this inward motion of the “inner disk radius” reaches the black hole horizon
- Finally restoring the situation with we began in (a)



ESTIMATES OF THE GALACTIC BLACK HOLE POPULATION

- The absolute numbers of neutron stars in the Galaxy can be estimated easily
- There should be at least 100–200 million neutron star remnants in our Galaxy at this time
- One method of estimating the relative numbers of black holes and neutron stars is to use the theory of stellar evolution and death
- Massive stars in the range $10-20\ M_{\odot}$ make neutron stars and $>20\ M_{\odot}$ make black holes
- Using estimates of the stellar initial mass function, derived in 1955 by Edwin Salpeter, massive stars should be making black holes at a rate about only 2.5 times less often than neutron stars
- The current number of black holes in the Galaxy is about 80 million
- However, that does not seem to be the case

ESTIMATES OF THE GALACTIC BLACK HOLE POPULATION

- Another method of doing this is to directly compare the number of neutron stars and black holes currently known
- 85% of the known XRBs are neutron star system while the others are black hole system, which leads to $6{:}1$ ratio
- However, the distributions of types of sources are so different that this result probably is an oversimplification
- The formation and evolution of LMXBs and HMXBs are so different
- HMXBs are made recently while LMXBs are formed early in the history of the Galaxy
- The LMXB statistics also are difficult to interpret
- There are about 3 times as many LMXB neutron star systems as black hole systems, but there are about equal numbers of transient X-ray novae
- This would imply a rather broad range in the numbers
- of black holes – from 0.3 to 1.0 times the numbers of neutron stars in the Galaxy

ESTIMATES OF THE GALACTIC BLACK HOLE POPULATION

- The LMXB statistics also are difficult to interpret
- There are about 3 times as many LMXB neutron star systems as black hole systems, but there are about equal numbers of transient X-ray novae
- This would imply a rather broad range in the numbers of black holes – from 0.3 to 1.0 times the numbers of neutron stars in the Galaxy
- The HMXBs seem to be a rather homogeneous class
- There are at least 20 times more recently made neutron stars in high-mass X-ray binaries than black holes
- This would mean that the current number of stellar-mass black holes in the Galaxy is only 10 million and that stars do not begin producing black holes until their initial masses are above $\sim 50\ M_{\odot}$

ESTIMATES OF THE GALACTIC BLACK HOLE POPULATION

- Why the theoretical estimation is inconsistent with the observation?
- The most likely explanation is that the theoretical estimate does not take into account the high stellar wind mass loss that occurs in present-day (Population I) high-mass stars
- During the evolution of the massive stars, the atmosphere absorb the luminous radiation from the hot massive star, the star’s mass is blown away
- When the core collapse, the $20-50\ M_{\odot}$ stars may behave like $10-20\ M_{\odot}$, producing neutron stars instead of black hole
- Current rate of black hole formation is somewhere between one every $250\ yr$ and one every $2000\ yr$
- If the rate is constant over the life of galaxy, the current number of black holes would be roughly 5-40 million
- But the star and black hole formation rate were much higher when the Galaxy was first born, we will take a reasonable number to be about 15 million