2. Outflows and Jets in Cvs (Pulsars), XRBs and microquasars.

Daniele Dallacasa
Cataclysmic variable stars (U Geminorum Stars)

CVs subdivided into several smaller groups, often named after a bright prototype star characteristic of the class. The classes, which can overlap, include SS Cygni, U Geminorum, Z Camelopardalis, SU Ursae Majoris, AM Herculis, DQ Herculis, VY Sculptoris, AM Canum Venaticorum, and SW Sextantis.

Relatively easy to discover:
- usually quite blue objects (whereas the majority of stars are red)
- Variability is often quite rapid and strong
- Strong UV or even X-ray emission, peculiar emission lines are other typical properties

Several hundred cataclysmic variables are known

Binary star containing a white dwarf and a companion star
(usually a red dwarf, in some cases another white dwarf or a slightly evolved star (subgiant)
Stars close to each other:
– gravity of the WD distorts and accretes matter from the secondary
– in most cases, infalling matter forms an UV and X-ray emitting accretion disk
– disk may be instable producing dwarf nova outbursts, when a portion of its material falls onto the WD
during the accretion process, mass is accumulating on the white dwarf surface. Usually the donor star is rich in H; in many cases, the density and T at the bottom of the accumulated H layer eventually rises high enough to ignite nuclear fusion reactions, burning the bulk of the H layer to He in a short time.

This is seen as a nova outburst.
– the outer parts of the H layer and some of the fusion products are ejected to ISM
– If the accretion continues long enough to bring the WD to the Chandrasekhar limit, the increasing interior density can ignite runaway C fusion and trigger a Type Ia SN explosion, which completely disrupts the WD
In some cases the **B field of the WD is strong enough** to disrupt the inner accretion disk or even prevent disk formation altogether.

Magnetic systems often show strong and variable polarisation in their optical light, and are therefore sometimes called

**intermediate polars** *(DQ Herculis)* (in case of a partially disrupted disk) or **polars** *(AM Herculis)* (in case of prevented disk formation).*
Cataclysmic Variables: \((10^6 \text{ in the Galaxy})\)

**Classification:**

- **Novae**
- **Dwarf Novae**
- **Intermediate Polars**
- **Polars**

Pair with an evolved star (WD) accreting material from a
red dwarf: \(M \sim 0.1\) about solar composition,
cooler surface than that of the sun

They are close: distance less than 700000 km (sun radius!)
- they are unresolved by earth (space) observations
- images are from "artist's impression"

\[
D = 1.1 \left( \frac{P_{\text{orb}}}{3 \text{ hr}} \right)^{2/3} \left( \frac{M_{\text{WD}} + M_{\text{RD}}}{M_{\text{sun}}} \right)^{1/3} R_{\text{sun}}
\]

short period: \(~\) hours
Blue-shifted profiles as signatures of outflows

Observed outflows of \( \dot{M} \sim 10^{-11} M_{\text{sun}} \text{ yr}^{-1} \)

with observed velocities \( v \sim 3000 \text{ km s}^{-1} \)
Red star is close and then is tidally distorted and gas (plasma) stripped mass transfer in a "standard" accretion disk (if no significant B)

spiralizing gas radiates its gravitational potential energy away and getting hotter and hotter

Most of the energy is radiated in the UV

The disk outshines the whole system also in the optical
Dwarf Novae

Outbursts due to increased accretion rate ($M_{\text{acc}} \sim 10^{-8}$ vs. $10^{-11} M_{\odot}/\text{yr}$)

2-6 magnitudes brighter (6-100 times more luminous)

The more frequent the outburst, the less prominent

$V1159\text{Ori}$ bursts every $\sim 4$ days with $m \sim 2$

$WZ\text{Sgr}$ bursts every $\sim 30$ yrs with $m$ of several magnitudes
Novae

Outbursts due to increased nuclear burning on WD surface

6-19 magnitudes brighter (100-10,000,000 times more luminous)
Outbursts every $\sim 10^5 \text{ yr}$

Larger $\Delta m$, faster decay
Most of the strongly X-ray emitting CVs turned out to have a magnetic WD primary (some are known to have a B field $\sim 10^8$ stronger than that of the Earth). The accreting material is ionized $\Rightarrow$ the magnetic field drives the flow.

The geometry of accretion is very different in these magnetic CVs: accretion disks are truncated or absent.

In these cases, accretion is close to vertical, along the magnetic field lines, resulting in a stronger shock and stronger X-ray emission than when accretion is via a disk.

Magnetic CVs have been discovered mostly through their X-ray emission over the last 30 years.
Intermediate polar (DQ Herculis)

Alfven radius

- Secondary
- Inner Disc
- Accretion Disc
- Mass Transfer Stream
- Bulge
- Magnetic White Dwarf
- Orbital Motion
**Polar (AM Herculis):**
the magnetosphere drives the accretion
the ionized gas follows fields lines of the WD during the whole inter-star trajectory
(the Alfven radius exceeds L1)

Bremsstrahlung

Cyclotron (semirelativistic electrons and B field)

(Inverse) Compton cooling
Possible evolution of CVs:

The mass transfer make the WD heavier and heavier and possibly smaller and smaller.

The magnetic field conservation makes the B field stronger and stronger.

It is possible that DN and N become Polars.
The fate of matter leaving the system:

Dwarf Novae:
Stellar wind with enhancements during/after outbursts

Classical Novae (& Recurrent Novae):
external shell (H-burning) ejected during/after outbursts, quiescent stellar wind

Polars:
Magnetically driven accretion, only very fast charged particles may leave, quiescent stellar wind
- Spotted diffuse emission is from SNR
- More diffuse bremsstrahlung from the Galaxy hot corona
Neutron stars

What happens in case the compact object is or gets more massive?

\[
\text{Mass } \geq 1.4 M_{\text{sun}} \\
\text{Diameter } \sim 15 \text{ km}
\]

Neutron stars: compact objects created in the cores of massive stars during SN explosions. The core collapses and crushes together every proton with a corresponding electron turning each electron-proton pair into a neutron. The neutrons can often stop the collapse and remain as a neutron star.

Neutron stars can be observed occasionally: Puppis A – above – an extremely small and hot star within a SNR. They are more likely seen when they are a pulsar or part of an X-ray binary.
The history of Neutron stars

Chandrasekhar (1931) White dwarfs collapse at $> 1.44 \text{ Msun}$

Baade & Zwicky (1934) proposed:
- existence of neutron stars
- their formation in supernovae: radius of approximately 10 km

Oppenheimer & Volkoff (1939)
- Evaluated first equation of state
  - Mass $> 1.4 \text{Msun}$
  - Radius $\sim 10\text{ km}$
  - Density $> 10^{14} \text{g cm}^{-3}$

Pacini (1967) proposed:
- electromagnetic waves from rotating neutron stars
- such a star may power the Crab nebula
  - i.e. **PULSARS**
Neutron stars are about 10 km in diameter and have the mass of about 1.4 times that of our Sun. This means that a neutron star is so dense that on Earth, one teaspoonful would weigh a billion tons! Because of its small size and high density, a neutron star possesses a surface gravitational field about 300,000 times that of Earth.

Neutron stars are one of the possible ends for a star. They result from massive stars which have mass greater than 4 to 8 times that of our sun. After these stars have finished burning their nuclear fuel, they undergo a supernova explosion. This explosion blows off the outer layers of a star into a beautiful supernova remnant. The central region of the star collapses under gravity. It collapses so much that protons and electrons combine to form neutrons. Hence the name "neutron star".

Neutron stars may appear in supernova remnants or in x-ray binaries with a normal star. When a neutron star is in an x-ray binary, astronomers are able to measure its mass. From a number of such x-ray binaries, neutron stars have been found to have masses of about 1.4 times the mass of the sun. Astronomers can often use this fact to determine whether an unknown object in an x-ray binary is a neutron star or a black hole, since black holes are more massive than neutron stars.
PULSARS: a digression
PULSARS: a digression
**PULSARS: a digression**

Duty cycle is typically 5%
Individual pulses very variable in intensity
Stable profile if several hundred pulses added
Strongly linearly polarised

Monotonic polarisation position angle swing through the pulse implies the origin is near a magnetic pole
Much more complex polarisation characteristic in msp's indicating more complex field
Very high brightness temperature implies coherent emission
Drifting subpulses
Mode changing

Typically $10^{12}$ Gauss for normal pulsars
Consistent with magnetic flux conservation during stellar collapse
Typically $10^6$-$10^8$ Gauss for millisecond pulsars
Gravity dominates stellar structure
B field dominates exterior

\[
\frac{\text{Electrostatic force}}{\text{Gravitational force}} = \frac{e\Omega rB/c}{GMm/r^2} \sim 10^{12}
\]

Stellar surface is so small that observed emission is dominated by the magnetic field.
The electromagnetic wave generated by the misaligned rotating dipole causes loss of rotational energy and accounts for the observed slowdown

Only field lines inside light cylinder are closed
Particles are constrained move along field lines
Neutron stars

Chandrasekhar (1931) [8]
White dwarfs collapse at > 1.44 Msun

Baade & Zwicky (1934) [1] proposed:
existence of neutron stars
their formation in supernovae
radius of approximately 10 km

Oppenheimer & Volkoff (1939) [26]
Evaluated first equation of state
Mass >1.4Msun
Radius ~ 10km
Density > 1014g cm⁻³

Pacini[1967] proposed:
electromagnetic waves from rotating neutron stars
such a star may power the Crab nebula
\[ \frac{dE}{dt} = \frac{2}{3} \frac{1}{c^3} \frac{d^2 m}{dt^2} = \frac{2}{3} \frac{1}{c^3} \omega_{NS}^4 (m_o \sin \alpha)^2 \]

\[ m \approx H_{NS} R_{NS}^3 \]

source of emission: kinetic energy:

\[ \frac{dK_{NS}}{dt} = I_{NS} \omega_{NS} \dot{\omega}_{NS} \]

\[ \dot{\omega}_{NS} = \frac{2}{3} \frac{1}{c^3} \frac{\omega_{NS}^4 (m_o \sin \alpha)^2}{I_{NS}} \]

\[ \dot{\omega}_{NS} \sim \omega^n \]

\[ P \dot{P} = \frac{8\pi^2}{3} \frac{(m_o \sin \alpha)^2}{c^2 I_{NS}} \]
Energy budget:
\[ \frac{dK_{NS}}{dt} \approx 10^{30} - 10^{33} \text{erg s}^{-1} \]

Magnetic field on the neutron star surface:
\[ H_{NS} = \sqrt{\frac{3 c^2 I_{NS}}{8\pi^2 R_{NS}^6}} P \dot{P} \]

Radio luminosity about 1% of the total energy extracted from rotation

[Crab pulsar has 20%!]

Maximum Energy for particles

\[ \epsilon_{\text{max}} \approx \Delta \Phi_{\text{max}} q \approx \frac{3 \times 10^{12}}{P} \frac{H}{10^{12}} \text{eV} \]

\[ \gamma_{\text{max}} \approx \frac{6 \times 10^6}{P^2} \frac{H}{10^{12}} \]

Emitted photon at

\[ \nu = \frac{3c}{2R_c} \gamma^3 \]

\( \nu \approx 10^{25} \text{ Hz} \) immediate pair production

iterative process inducing a **pair cascade**

with e\(^+\) and e\(^-\) at progressively lower frequencies

As the pulsar age, the rotation and the magnetic field decrease and the cascade is not efficient anymore.

The pulsar turns of as enters the "death valley"
Evolution of period and its derivative

PSR J2144-3933
$P = 8.5 \text{ s}$
### PULSARS: the end of digression

http://www.jb.man.ac.uk/research/pulsar/Education/Sounds/sounds.html

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X-ray binaries: a cartoon

- Mass-donating companion star (IR-optical)
- Mass-flow
- Accretion disc (optical - soft X-rays)
- Accreting neutron star or black hole
- ‘Corona’ (hard X-rays)
- Jet (radio - ?)
- Companion
- Accretion disc
- Corona
- Radio infrared optical soft-X hard-X gamma-ray

\[ \Gamma > 1 \]
To date, about 30 XRB are known to possess substantial radio emission.
X-ray binaries: consequences

High brightness temperature
Non-Thermal (power-law) spectra
Linear polarisation

\[ \beta_{\text{obs}} \sim \left[ \frac{\mu}{170 \text{ mas/day}} \right] \left[ \frac{d}{\text{kpc}} \right] = \frac{\beta_{\text{true}} \sin \theta}{1 \mp \beta_{\text{true}} \cos \theta} \]

\[ \beta_{\text{true}} \cos \theta = \frac{\mu_{\text{appr}} - \mu_{\text{rec}}}{\mu_{\text{appr}} + \mu_{\text{rec}}} \]

\[ \tan \theta = \frac{2d}{c} \cdot \frac{\mu_{\text{appr}} \mu_{\text{rec}}}{\mu_{\text{appr}} - \mu_{\text{rec}}} \]

\[ \frac{S_{\text{appr}}}{S_{\text{rec}}} = \left( \frac{\delta_{\text{appr}}}{\delta_{\text{rec}}} \right)^{k+\alpha} = \left( \frac{1 + \beta_{\text{true}} \cos \theta}{1 - \beta_{\text{true}} \cos \theta} \right)^{k+\alpha} \]
Flares: found in both transients and persistent (radio sources)

Rise: Synchrotron bubble? Injection/acceleration?

Decay: Adiabatic expansion? Synchrotron + IC losses?
SS433/W50 (@4.7+/-0.3 kpc)

First noted in the '60s by Stephenson and Sanduleak (included in a catalog of stars with unusual features in their spectra). As the 433rd object in Stephenson and Sanduleak's catalog, it became known as SS 433.

A massive, hot star is locked in a mutual orbit with a compact object. Material transfers from the massive star into an accretion disk surrounding the compact object blasting out two jets of ionized gas in opposite directions at about 1/4 the speed of light!

Radiation from the jet tilted toward the observer is blue-shifted, while radiation from the jet tilted away is red-shifted. The binary system itself completes an orbit in about 13 days while the jets precess (wobble like a top) with a period of about 164 days.

Radio / Optical SNR W50
Time variability vs frequency

Flux density, Jy

MAY 1996

SS433

2.7 cm
3.9 cm
7.6 cm
13. cm
31. cm
SS433 is the **ONLY XRB** with IR, optical, X-ray emission lines in the spectrum associated with the jet.

\[ v \sim 0.26c \] is lower than in other sources

→ a proton/electron jet? (all the others have \( e^+/e^- \) jets...??)

a small fraction of the total mass can escape the system

Baryonic components in jets are difficult to observe
SCO X-1 monitored at radio wavelengths (VLBA)

Observed for 2.3 days and images every 50', interpolation every 15'

Discovered in 1962 on a rocket flight from White Sands Range (NM)
Neutron star + Sun-type secondary @ 9000 ly from Earth
Separation 0.001 AU
Period 18h53m
Maximum disk Temperature (~100 million K)
Magnetic Field perpendicular to the disk
GRS 1915+105

Low/Hard

High/Soft

Low/Hard

INFRARED

RADIO

Sept 09, 1997

Normalized Luminosity

Hardness

UT Time (hours)
Internal shock

\( \Gamma > 2 \)

\[ i \]

\[ ii \]

Steady Jet

\[ \Gamma < 2 \]

VHS/IS

sketch of the very inner part of the system
Disk status and structure in terms of accretion

- high/low accretion rate
- large/small disk

Hot corona largely depends on the amount of high energy radiation
Spectral Energy Distribution of Cygnus X-1
Low mass XRBs

High mass XRBs

LM-XRBs are concentrated in the Galactic bulge
Emission from steady jets

no direct evidence of X-rays from steady jets,
but \( L_R \sim < L_X >^{0.7} \)

changes in the SED: correlation between radio and X-rays
(related to accretion rather than same process???)

X-rays are more likely from IC on softer photons in a hot
(100keV) plasma rather than optically thin synchrotron
### Categorie di Getti/Outflows:

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