Accretion on to Magnetic White Dwarfs

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Outline

Observations

In some Binary Systems we observe quite interesting features:

- Strongly polarized emission (up to 60 % circular polarisation in the optical)
- Unexpectedly long soft X-Ray component
- Highly variable lightcurves in optical and X-Ray

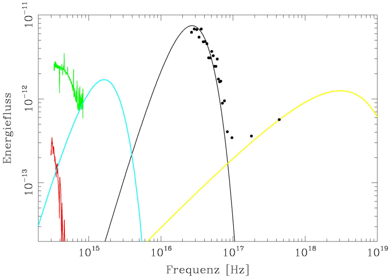
$\Rightarrow$ Strong Influence from a magnetic field on the binary system

Example1 : AM Herculis type

Spectrum of V 393 Pavonis

The νF_ν over ν plot shows :

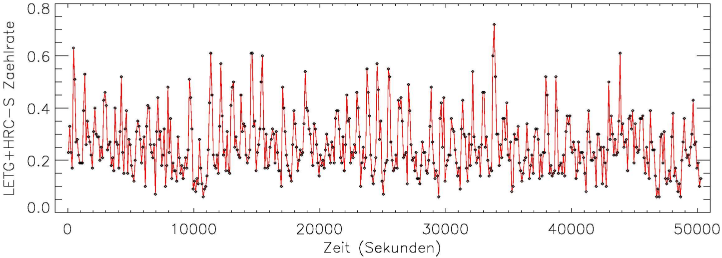
- Measured optical spectrum (green)
- Measured X-Ray spectrum (black dots)
- Measured optical / IR spectrum from Secondary (red)
- Expected observations from the WD (cyan)
- Blackbody fits (yellow, black line)



From: V. Burwitz: X-ray and optical properties of ROSAT discovered magnetic cataclysmic variables (1997)

Example 2: PQ Geminorum
RE 0751+14

- Some binary systems show enormous oscillations in their lightcurve:



Observations from Chandra X-Ray Observatory

Where do those effects come from ?

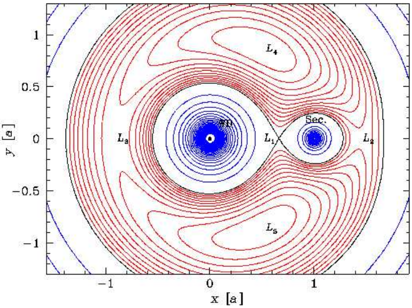
White Dwarf and Secondary

- A system consisting of an accreting white dwarf and a secondary star in close orbit is called Cataclysmic Variable (CV)
- The secondary often is a M-class mean sequence star of about $0.2 - 0.5\, M_\odot$
- The white dwarf got more mass and is hotter than the Secondary $(8000 - 60000\, K)$
- A small separation is observed in most systems

$\Rightarrow$ high rotation periods

Accretion Stream

- Consists of ionised matter from the secondary
- Accretion happens mostly due to Roche Overflow
- Follows a lightly curved trajectory due to the coriolis force
- Falls on magnetic WD with free-fall velocity:
  $v_{ff} = \sqrt{\frac{2G \cdot M_{WD}}{r}} \approx 2000 - 4000\ \frac{km}{s}$



Roche-equipotential-lines for q=5 J.Kube

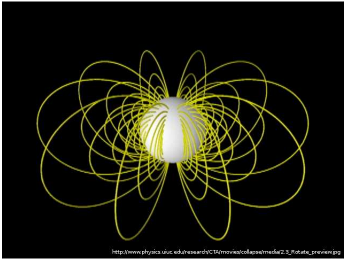
From: http://www.hs.uni-hamburg.de/DE/Ins/Per/Vrielmann/DLS/roche.gif

Magnetic Field of the WD

in First Approximation

- Both stars have a magnetic field
- The magnetic flux is roughly conserved during star evolution: $B \cdot R^2 \approx const$
- $\Rightarrow$ High field strengths up to $\approx 20000\, T$ (20 MG) near the WD
- Magnetic field is approximated as a Dipole:

$$\vec{B} \approx \frac{\vec{\mu}_D}{r^3}$$



From: http://www.physics.uiuc.edu/research/CTA/movies/collapse/media/2.3_Rotate_preview.jpg

Coupling of Magnetic Field and Accretion Stream

- How do the magnetic field and the accretion stream interact ?
- From plasma physics we obtain the Magnetic Pressure:

$$P_{mag} = \left(\frac{4\pi}{\mu_0}\right) \cdot \frac{B^2}{8\pi} \overset{dipol}{=} \left(\frac{4\pi}{\mu_0}\right) \cdot \frac{\mu^2}{8\pi r^6}$$

- and the Ram Pressure :

$$P_{ram} = \rho \cdot \vec{v}^2 \propto \left[\frac{E_{kin}}{V}\right]_{\vec{v}}$$

- Magnetic Field takes over at:

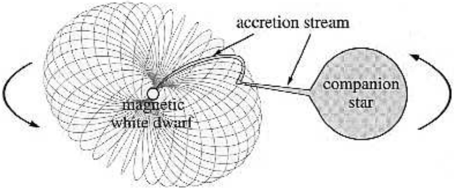
$$P_{ram} \approx P_{mag}$$

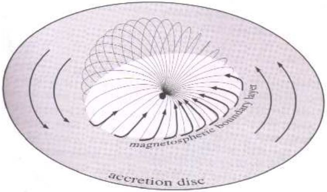
- Alvén Radius:

$$r_a = \left(\frac{\mu^2}{\mu_0} \cdot \frac{1}{2\rho v^2}\right)^{\frac{1}{6}} \overset{Mass\ cons.}{=} \sqrt{\frac{\mu^2}{\mu_0} \cdot 8\pi^2 \frac{\rho}{\dot{M}^2}}$$

Visualisation

- For strong magnetic fields of the WD no disc is formed, instead the accretion stream follows the field lines directly
- In some cases a truncated accretion disc will form





From: Frank, King, Raine Accretion Power in Astrophysics

Spin Periods and Angular Momentum

- System has an orbital period : P_{orb} ; the WD a spin period : P_{spin}
- Therefore modulations should be observed
- Accretion stream transfers angular momentum to WD

$$\Rightarrow \text{Spin-up ?}$$

- Consider interaction of magnetic moments of the two stars!

$$(\vec{M} = \vec{m}_m \times \vec{B})$$

- Magnetic moments can balance transfer of angular momentum, if interaction is strong enough

Systems with Strong Magnetic Interaction

Polar CV's

In general, systems with strong magnetic field of the WD
($B_\star \approx 3 \cdot 10^3\ T; \mu \approx 3 \cdot 10^{24}\ \frac{T}{m^3}$) :

- Synchronise orbital period and spin period of the WD, due to magnetic interaction
- Don't have accretion discs
- Can be identified through strong polarisation in optical wavelength
- Are called Polars or AM Her Stars

Systems with Weaker Magnetic Interaction

Intermediate Polar CV's

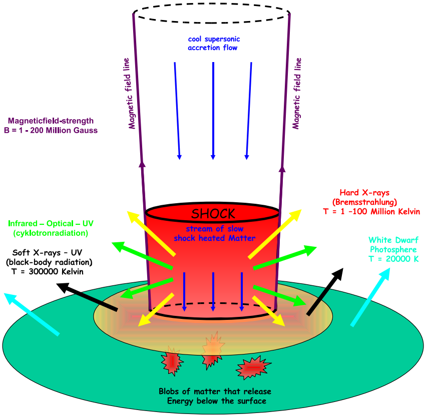
In general, system with weaker magnetic field show :

- Low Interaction between magnetic moments
- $\Rightarrow$ Spin Up, due to transfer of angular momentum
- No synchronised state of the rotation periods, but rotation at high velocities
- A truncated accretion disc, as magnetic pressure can't control the plasma far enough

These are called Intermediate Polars or DQ Her systems

Standard Model for Accretion Column
Energy Source and Accretion Blob

- Accretion stream is channeled to the magnetic poles on the WD's surface
- Plasma has supersonic speed: $v_{plasma} \approx v_{ff} = \sqrt{\frac{2G \cdot M_{WD}}{r}}$
- Plasma stops where gas pressure equals ram pressure.
- Strong shock due to deceleration, $E_{kin} \rightarrow E_{therm}$
- Heating to $> 10^8 K$



From: V. Burwitz: X-ray and optical properties of ROSAT discovered magnetic cataclysmic variables (1997)

Bremsstrahlung

- Infalling proton encounters electrons of the WD‘s atmosphere
- Acceleration of charges in electromagnetic fields leads to thermal bremsstrahlung
- Radiation is optical thin, with energies :

$$10\, keV \leq kT_{Br} \leq kT_{Shock}$$

- $\Rightarrow$ Emission of hard X-Rays
- Most important cooling mechanism in most CV’s

Cyclotron Radiation

- Thermal motion makes electrons gyrate around magnetic field lines
- Cyclotron frequency of n-th order : $n \cdot \omega_{cyc} = n \cdot \frac{e \cdot B}{m_e c}$
- Resulting Polarisation is strong evidence for magnetic controlled accretion
- Distance between lines gives magnetic field strength:

$$\omega_{cyc} = \omega_{n+1} - \omega_n = \frac{e \cdot B}{m_e c}$$

- Higher orders in optical - UV, fundamental in IR wavelength

Reprocessed radiation and Line Emission

- Bremsstrahlung heats the WD's surface: $T \approx 10^6\ K$
- $\Rightarrow$ Radiation of EUV and Soft X-Rays; (Quasi-) Blackbody Component reprocessed in WD's surface
- UV and X-Rays illuminate Accretion Stream, disc and parts of the Secondary
- $\Rightarrow$ Excitation and photo-ionization of matter

Several emission lines are detected:

- Paschen lines @ near IR
- Balmer, HE 1, HE 2 @ visible
- Lyman L_α, highly ionized C, N and Si @ UV

Photospheric Emission

- The M-class Secondary emitts in near IR
- Below 4000 K molecular absorbtion of e.g TiO, VO and H_2O takes place
- The WD emitts in near UV; $8000 - 60000\,K$
- Typical broadened H and He lines are observed
- In low state Zeeman troughs are observed
- $\Rightarrow$ Determination of magnetic field
- Sometimes the heated photosphere from accretion region up to $\approx 10000\,K$ is seen in UV

Summary of Radiation Processes

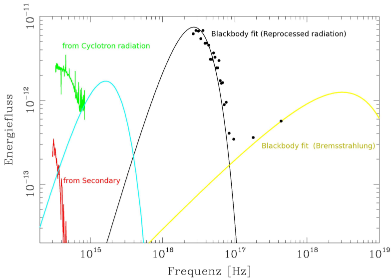
- Thermal Bremsstrahlung → Main cooling process
- Cyclotron radiation → Gives field strength in distance to the WD
- Reprocessed radiation from the WD's surface → Composition of the WD
- Photospheric and line emission → Composition of Secondary and accretion stream
- Zeeman effect in low state gives magnetic field strength @ WD's surface

Comparison of Model and Observations

Energy flux from Polar: V 393 Pavonis

The Model gives us:

- Secondary: Spectrum @ IR - visible
- Cyclotron Radiation @ visible
- Reprocessed Radiation @ soft X-Rays
- Bremsstrahlung @ hard X-Rays

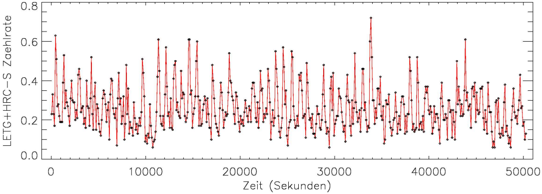


From: V. Burwitz: X-ray and optical properties of ROSAT discovered magnetic cataclysmic variables (1997)

IP : PQ Geminorum (RE 0751+14)

- IP rotates fast; (transfer of angular momentum)
- Accretion onto a small fraction of the surface (magnetic pole)
- $\Rightarrow$ Lighthouse effect

$$\frac{1}{P_{beat}} = \frac{1}{P_{spin}} - \frac{1}{P_{orb}}$$

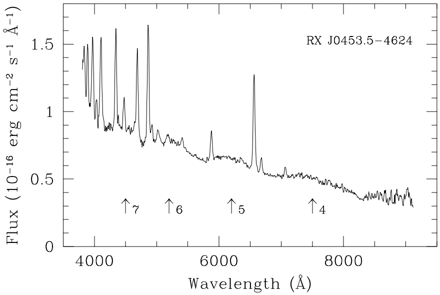


Observations from Chandra X-Ray Observatory

Observations of Cyclotron Radiation

- Cyclotron Radiation is expected
- Calculations show: fundamental frequency is absorbed in accretion column
- Higher orders are seen and give magnetic field strength

$$B = 2\pi \cdot \frac{m_e c^2}{e} \left(\frac{1}{\lambda_{n+1}} - \frac{1}{\lambda_n} \right)$$



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Summary

There are two types of cataclysmic variables with non neglectable magnetic field:

- Polars, with strong magnetic field, but without accretion disc
- Intermediate Polars, with accretion disc, but with weaker magnetic field

further the accretion takes place only on the magnetic poles of the White Dwarf. The reprocessed radiation from the poles is seen in soft X-Ray Spectrum.

Literature

- V. Burwitz: X-ray and optical properties of ROSAT discovered magnetic cataclysmic variables (1997)
- Frank, King, Raine: Accretion Power in Astrophysics ; Cambridge 2002
- Kolb : Interacting Binary Stars ; The Open University 2002
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