Compact rotating objects (BHs and Neutron Stars) are the engines of some of the most relevant phenomena in High Energy Astrophysics, from Pulsar (PSR) to GRB. Today, thanks to the development of numerical tools for GR-MHD we are able to models these systems and relate their observed properties to the otherwise unobservable engine. The observed features and dynamics in Pulsar Wind Nebulae (PWNe) can be directly related to the wind structure and ultimately to the PSR magnetosphere. The character of the prompt emission, of the afterglow, the presence of an associated supernova (SN), and the environment, all characterize and constrain the possible central engine of Long and Short Gamma Ray Bursts (GRBs). For GRBs the two leading models are the “collapsar” and the “millisecond protomagnetar.” I will briefly review the various criteria that any model must satisfy, and I will illustrate the key ideas behind both the collapsar and millisecond magnetar, with their strengths and weakness, especially in the light of the recent observation of the so called "late activity".
Relativistic Outflows from Compact Objects: PWNe & GRBs

Niccolo' Bucciantini

INAF Osservatorio Astrofisico di Arcetri
http://www.arcetri.astro.it

L. Del Zanna, D. Volpi, B. Olmi, S. Komissarov, N. Camus, B Metzger, E. Quataert
Prototypical central engine
The pulsar magnetosphere

\[ R_{NS} = 10 \text{km} \]
\[ P = 0.001 - 7 \text{s} \]
\[ B_{surf} = 10^{8-12} \text{G} \]

Unipolar inductor (AGN, GRB, Magnetar)
EM extraction of rotational energy.

Acceleration of particle pair plasma-
ions from the surface:
Initial Lorentz factor \( \sim 100 \)
Cold wind (Sync. losses)
The FF limit

No exact solution even for the simple monopole-like case

\[ \sigma \approx \Phi^2 \Omega / \dot{M} \quad \Rightarrow \quad \gamma_\infty \sim \sigma^{1/3} \quad \sigma_\infty \sim \sigma^{2/3} \]

Conversion of magnetic energy is logarithmic after the fast p.

No collimation for a relativistic wind

\[ \gamma \gg 1 \Rightarrow \rho_q \bar{E} + \vec{j} \times \bar{B} \approx 0 \]

Force Free Pulsar Equation

\[
(1 - \rho^2 \Omega^2) \left[ \frac{\partial^2 f}{\partial \rho^2} + \frac{1}{\rho} \frac{\partial f}{\partial \rho} + \frac{\partial^2 f}{\partial z^2} \right] - \frac{2}{\rho} \frac{\partial f}{\partial \rho} = -A \frac{dA}{df} + \rho^2 \Omega \frac{d\Omega}{df} \left[ \left( \frac{\partial f}{\partial \rho} \right)^2 + \left( \frac{\partial f}{\partial z} \right)^2 \right].
\]
Wind models

Force-free (Contopulos et al 1999, Gruzinov 2005, Spitkovsky 2006 + ......)
RMHD (Bogovalov 2001, Komissarov 2006, Bucciantini et al. 2006 + .......)
Striped Wind - More Geometry

Bogovalov

Spitkovsky
The global wind
Energy Losses

The wind luminosity has a latitudinal structure that depends on the magnetic inclination of the pulsar.

$$4\pi d\frac{d(L/L_0)}{d\omega}$$

It also depends on the Efficiency of the gap to establish FF regime.

Tchekhovskoy et al. 2012

Li et al. 2011
In a striped wind reconnection of alternating fields can accelerate particles.

**HD shock**

**Tearing modes reconnection**

**Hard spectrum**

**Fast-magnetosonic precursor**
Interaction

I

PWNe
Pulsar Wind Nebulae

- PWNe are hot bubbles (plerions) of relativistic particles and magnetic field emitting non-thermal radiation (synchrotron - IC) from Radio to $\gamma$-ray.
- Originated by the interaction of the ultra-relativistic magnetized pulsar wind with the expanding SNR (or with the ISM)
- Crab Nebula in optical: central amorphous mass (continuum) + external filaments (lines)
Pulsar Wind Nebulae

- PWNe are hot bubbles (plerions) of relativistic particles and magnetic field emitting non-thermal radiation (synchrotron - IC) from Radio to $\gamma$-ray.
- Originated by the interaction of the ultra-relativistic magnetized pulsar wind with the expanding SNR (or with the ISM)
- Crab Nebula in optical: central amorphous mass (continuum) + external filaments (lines)
Cartoon
Cartoon

ISM
Outgoing Shell
\[ V_{\text{snr}} \sim 0.003-0.01c \]
SNR Shell
The cavity is swept by the PRS wind.

Outgoing Shell
$V_{\text{snr}} \sim 0.003-0.01c$
SNR Shell

ISM
Outgoing Shell
\[ V_{\text{snr}} \approx 0.003-0.01c \]
SNR Shell

The cavity is swept by the PRS wind

\[ V_{\text{sn}} \ll V_{\text{wind}} \]

The wind is slowed down in a termination shock
A pulsar wind nebula is formed

Termination Shock
The cavity is swept by the PRS wind.

Outgoing Shell $V_{snr} \sim 0.003-0.01c$
SNR Shell

$V_{sn} \ll V_{wind}$
The wind is slowed down in a termination shock
A pulsar wind nebula is formed

Compressed magnetic field is mostly toroidal and press along the axis
Crab Nebula - a prototype

Lifetime: X-rays -- few years, γ-rays -- months. Need energy input!
Crab pulsar: $E_K = 5 \times 10^{38}$ erg/s, 10-20% efficiency of conversion to radiation.

Max particle energy $> 3 \times 10^{15}$ eV, comparable to pulsar voltage.
Nebular shrinkage indicates one accelerating stage:
require $10^{38.5} - 10^{39}$ e± /s, radio mystery
PSR also injects B field into nebula ($\sim 10^{-4}$ G)

$S_\nu \propto \nu^{-0.3}$ (radio); $\nu^{-1.0}$ (X-ray); break

Log flux vs. log frequency
Polarization - magnetic field

Old nebulae interacting with ejecta - distorted stretched field in the back direction

Vela, Dodson et al 03

G106.6+29, Kothes et al 06
Polarization - magnetic field

Old nebulae interacting with ejecta - distorted stretched field in the back direction

Vela, Dodson et al 03
G106.6+29, Kothes et al 06
Fine structures

- Vela pulsar (*Helfand et al.*, 2001; *Pavlov et al.*, 2003)
The wind anisotropy shapes the TS structure. Downstream flow - equatorial collimation due to the TS shape:

- A: ultrarelativistic pulsar wind
- B: subsonic equatorial outflow
- C: supersonic equatorial funnel
- D: super-fastmagnetosonic flow
- a: termination shock front
- b: rim shock
- c: fastmagnetosonic surface
The wind anisotropy shapes the TS structure and flow pattern downstream due to:

- The TS structure shapes the flow anisotropy.
- A: ultrarelativistic pulsar wind flow
- B: subsonic equatorial outflow
- C: supersonic equatorial funnel
- D: super-fast magnetosonic flow
- a: termination shock front
- b: rim shock
- c: fast magnetosonic surface

$\sigma = 0.03$
Formation of polar jets by hoop stresses

- The global nebular flow changes with $\sigma$
- Flow is diverted to the axis when equipartition is reached
- For high magnetization ($\sigma > 0.01$) a supersonic jet is formed
- Equipartition must be reached inside the PWN

$\sigma=0.003$  $\sigma=0.01$  $\sigma=0.03$
Modeling a striped wind case

- Initial magnetic field with a narrow equatorial neutral sheet
- Dissipation in a striped wind
Comparison with Observations

Main torus
Inner ring (wisps structure)
Knot
Back side of the inner ring

No jet - Axisymmetric assumption

Hester et al. 1995
Komissarov & Lyubarky 2004
Comparison with Observations

Camus et al.
Comparison with Observations

Camus et al.
Time variability - wisps

- Wisp moving outward
- Year long limit cycle
- Variability in the knot
- Bubble in the jet $v \sim 0.6 \, c$

Variability in the knot structure
Jet feature moving at $0.6 \, c$

Local instabilities or global modes?

Slane 05, DeLaney 06
Instability of the shear layers creates eddies at the rim shock

Eddies are advected outward and a toroidal pressure wave is launched

There is no wave reflection from the boundary

Waves reflected on the axis modulate the TS shape

The equatorial channel is kink unstable
Instability of the shear layers creates eddies at the rim shock.

Eddies are advected outward and a toroidal pressure wave is launched.

There is no wave reflection from the boundary.

Waves reflected on the axis modulate the TS shape.

The equatorial channel is kink unstable.
MHD variability - High Energy

\[ t \text{(yr)} \]

\[ 20 \quad 22 \quad 24 \quad 26 \quad 28 \quad 30 \]

\[ 0 \quad -0.5 \]

\[ 52000 \quad 53000 \quad 54000 \quad 55000 \]

\[ \text{Time (MJD)} \]

\[ \text{F hotline (units)} \]

\[ 0.90 \quad 0.92 \quad 0.94 \quad 0.96 \quad 0.98 \quad 1.00 \quad 1.02 \quad 1.04 \]

\[ \text{Wilson-Hodge et al. 2010} \]

\[ \sim 2 \text{ yr Timescale} \]
Purely toroidal fields are unstable in 3D

However there is also continuous injection

Mizuno et al. 2010

Porth et al. 2013
Interaction

II

GRBs
Long GRBs

Bursts of Gamma-Rays

N. Bucciantini: Accretion and Outflows in Lyon 2014
Long GRBs

**Bursts of Gamma-Rays**

$E_p \sim 100$-200 KeV
Long GRBs

Bursts of Gamma-Rays

Ep ~ 100-200 KeV

Uniform Distribution
Cosmological Origin

2704 BATSE Gamma-Ray Bursts

Fluence, 50-300 keV (ergs cm⁻²)
Long GRBs

Bursts of Gamma-Rays

E_p \sim 100\text{-}200 \text{ KeV}

Uniform Distribution

Cosmological Origin

Variability up to ms

Variability timescale \sim \text{ ms} implies a compact stellar mass engine

Variability shorter than duration implies continuous injection
GRB are seen to scintillate in radio for several days after the burst.

For typical galactic ISM variation the scintillation radius of an extragalactic source is $\sim 1.0 \times 10^{17}$ cm.

This implies an expansion speed $\sim c$. 

Lorentz factor
GRB are seen to scintillate in radio for several days after the burst.

For typical galactic ISM variation the scintillation radius of an extragalactic source is \( \sim 1.0 \times 10^{17} \) cm.

This implies an expansion speed \( \sim c \).

Compactness Argument

Spectrum shows a non thermal power-law tail.

If the source is non relativistic the optical depth for pair production is large and one would expect a thermal spectrum.

Non-thermal spectrum \( \Rightarrow \) high Lorentz Factor \( \sim 100-1000 \).
Jets and SN connection

Evidence for collimation from so called “jet-breaks”

\[ t_j \approx 3.9(1 + z)E_{iso,53}^{1/3}n_0^{-1/3}(\frac{\theta_0}{0.2})^{8/3} \text{ days}, \]

The typical opening angle is \( \sim 10 \) deg
Jets and SN connection

Evidence for collimation from so called “jet-breaks”

\[ t_j \approx 3.9(1 + z)E_{iso,53}^{1/3}n_0^{-1/3}\left(\frac{\theta_0}{0.2}\right)^{8/3} \text{ days,} \]

The typical opening angle is ~ 10 deg

SN 1998bw and SN2003dh were coincident with GRBs within days.

\[ SN \text{ Ib/c} \]

SN are very energetic and bright:
- \( E_{\text{kin}} \sim 10^{52} \text{ ergs} \)
- \( V_{ej} \sim 2 \times 10^4 \text{ Km/s} \)
- 1M_{sun} of Ni^{56}
Constraints on the central engine

- High energy $\sim 10^{51-52}$ ergs $\rightarrow$ large energy reservoir
- $E_{\text{tot}} < E_{\text{iso}} \rightarrow$ collimation
- Millisecond variability $\rightarrow$ compact objects (BH or NS)
- $T/\delta T >> 1 \rightarrow$ quasi-steady energy injection (not an explosion)
- 100 sec duration of LGRB and SGRBEE $\gg$ engine timescale
- High energy non-thermal spectrum $\rightarrow$ relativistic outflows ($\Gamma > 100$)
- Late time activity $\rightarrow$ long lived engine

LGRBs

*Associated with young galactic population*

*Found in star forming regions of host galaxy*

*Associated with core-collapse events*
The core of a rotating massive star collapses to a black hole. Material far from the axis does not fall straight in but form an accretion disk. Dissipation in the disk converts kinetic energy into heat. Magnetic field power accretion (MRI). A jet is launched.

Energy can be extracted in various ways:
- Neutrino heating in the polar region
- Wind from the disk (Blandford-Payne)
- Angular momentum from BH (Blandford-Znajek)

Hawley et al.
The core of a rotating massive star collapses to a black hole.
Material far from the axis does not fall straight in but form an accretion disk.
Dissipation in the disk convert kinetic energy into heat.
Magnetic field power accretion (MRI).
A jet is launched.

Energy can be extracted in various ways:
- Neutrino heating in the polar region
- Wind from the disk (Blandford-Payne)
- Angular momentum from BH (Blandford-Znajek)
Properties of collapsar

Possible avenues to drive a GRB:

- v-v Annihilation driving a wind
- Disk wind powered by BP
- BZ extracting energy from the BH

**Pro**

- Collapse in high mass stars favors BH
- Jets are naturally associated with accretion disks
- Disk wind can give the correct Ni^{56} load
- Very high $\Gamma$ can be achieved in the jet
- Fragmentation of the torus can lead to late time accretion events (flares)
- Accretion can be sustained for a long time

**Cons**

- Need rapidly rotating BH
- There is a $J_{\text{max}}$ for the envelope
- $\Gamma$ is set by non-obvious mass loading
- Need ordered seed magnetic field
- Need a long surviving torus inside SN
- Direct collapse to BH not obviously produces SN shock

Barkov & Komissarov 2008
What is the role of the BH rotation? IS rotation important for the jet?

Kerr parameter $a > 0.5$ for efficient jet. At $\sim 1.5$ sec the jet is still non-relativistic.
Magnetars have fields ~ $10^{14-15}$ G
They might be born as fast rotators
Efficient dynamo implies $P \sim t_{\text{conv}} \sim \text{ms}$

**Pro**

NS are naturally associated to core collapse SN
Less angular momentum required than BH-AD
NS population can explain transition from asymmetric SNe to XRFs to GRBs
Magnetar can show energetic bursts

Millisecond magnetar have the correct energy

$$E_{\text{Rot}} \approx 2 \times 10^{52} \left( \frac{P}{1 \text{ ms}} \right)^{-2} \text{ergs}$$

Typical spin-down times are ~ 100-1000 sec

$$\dot{E} \approx 10^{49} \left( \frac{P}{1 \text{ ms}} \right)^{-4} \left( \frac{B_{\text{Dip}}}{10^{15} \text{ G}} \right)^2 \text{ergs s}^{-1}$$
Magnetars have fields $\sim 10^{14-15} \text{ G}$
They might be born as fast rotators
Efficient dynamo implies $P \sim t_{\text{conv}} \sim \text{ms}$

Millisecond magnetar have the correct energy
$$E_{\text{Rot}} \approx 2 \times 10^{52} \left( \frac{P}{1 \text{ ms}} \right)^{-2} \text{ ergs}$$

Pro
NS are naturally associated to core collapse SN
Less angular momentum required than BH-AD
NS population can explain transition from asymmetric SNe to XRFs to GRBs
Magnetar can show energetic bursts

Typical spin-down times are $\sim 100-1000 \text{ sec}$
$$\dot{E} \approx 10^{49} \left( \frac{P}{1 \text{ ms}} \right)^{-4} \left( \frac{B_{\text{Dip}}}{10^{15} \text{ G}} \right)^2 \text{ ergs s}^{-1}$$

Pulsars have relativistic winds
Magnetars have fields $\sim 10^{14-15}$ G
They might be born as fast rotators
Efficient dynamo implies $P \sim t_{\text{conv}} \sim \text{ms}$

Millisecond magnetar have the correct energy
$$E_{\text{Rot}} \approx 2 \times 10^{52} \left( \frac{P}{1 \text{ ms}} \right)^{-2} \text{ergs}$$

Pro
NS are naturally associated to core collapse SN
Less angular momentum required than BH-AD
NS population can explain transition from asymmetric SNe to XRFs to GRBs
Magnetar can show energetic bursts

Typical spin-down times are $\sim 100$-1000 sec
$$\dot{E} \approx 10^{49} \left( \frac{P}{1 \text{ ms}} \right)^{-4} \left( \frac{B_{\text{Dip}}}{10^{15} \text{ G}} \right)^2 \text{ergs s}^{-1}$$

Magnetars can have massive progenitors

Pulsars have relativistic winds

Westerlund I
Magnetar
Chandra X-Ray

Faintest Cluster Members are O7 (Clark et al 2014)
Extracting the energy via winds

- Core-Collapse SNe Produce **Hot** Proto-Neutron Stars that **Cool** Via $\nu$-Emission
  - $\sim 10^{53}$ ergs in $\tau_{KH} \sim 10-100$ s

- Neutrinos **Heat** Matter above the PNS Surface, Driving a Thermal Wind into the Evacuated Region Behind the SN Shock (Duncan et al. 1986).

Scheck et al
Core-Collapse SNe Produce **Hot** Proto-Neutron Stars that **Cool** Via \( \nu \)-Emission 
\(~10^{53} \text{ ergs in } \tau_{KH} \sim 10-100 \text{ s}\)

Neutrinos **Heat** Matter above the PNS Surface, Driving a Thermal Wind into the Evacuated Region Behind the SN Shock (Duncan et al. 1986).

**Regular PNS winds are not dynamically relevant for SN**
PNS spin-down

\[ P = 1 \text{ms}, \beta = 10^{15} \text{G} \]

- Mass Loss Rate
- Energy Loss Rate
- Angular Momentum Loss Rate

\[ 10^{51} \text{ ergs/s} \]

\[ 10^{48} \text{ ergs/cm}^2 \cdot \text{s} \]

\[ t(\text{sec}) \]

N. Bucciantini: Accretion and Outflows in Lyon 2014
PNS spin-down

Comparison of the losses for a free-wind case and the case of a PNS confined inside a SN progenitor.
PNS spin-down

Comparison of the losses for a free-wind case and the case of a PNS confined inside a SN progenitor.

Losses are not changes by confinement, same torque, free wind model for PNS evolution are reliable.
Comparison of the losses for a free-wind case and the case of a PNS confined inside a SN progenitor.

Losses are not changes by confinement, same torque, free wind model for PNS evolution are reliable

Less energy is extracted from the PNS. The PNS wind does not efficiently powers the SN.
Interaction with the progenitor

Recent numerical study investigates the transition from the matter dominated phase to the magnetic dominated phase.

Jet are ubiquitous feature originating from the confinement of a toroidally dominated magnetic field.

Dissipative processes affect the acceleration of the jet but not the collimation.
Properties of the Jet

Jet acceleration is more efficient than analytic radial estimates

Spindown-power of the PNS is carried by the jet
3D vs 2D

Instabilities of the jet (kink) reduce its penetration

The jet is still present but much weaker and broader than in 2D

Timescale and energetics?
MHD SN - Elongation

$t - t_b = 67.8\text{ms}$

Octant symmetry

Full 3D

Specific entropy $[k_b \text{ baryon}^{-1}]$

$10$ $8.25$ $6.5$ $4.75$ $3$

$2000\text{ km}$

$1000\text{ km}$

Mosta et al 2014
MHD SN - Elongation

Figure 1. Meridional slices (––plane; being the vertical) of the specific entropy at various postbounce times. The "2D" (octant 3D) simulation (leftmost panel). Mosta et al 2014.

Octant symmetry

$t - t_b = 67.8\text{ms}$

$2000\text{ km}$

$1000\text{ km}$

$t - t_b = 67.8\text{ms}$

$t - t_b = 120.0\text{ms}$

$t - t_b = 186.4\text{ms}$

Full 3D

Full 3D

Full 3D

Specific entropy $[k_{\text{b}} \text{ baryon}^{-1}]$

$10$ $8.25$ $6.5$ $4.75$ $3$

Mosta et al 2014
MHD SN - Elongation

Bipolar structure are found but no evidence of jets in 3D
nu-SNe have energy \(< 1e51 \text{ erg}\)

Situation is going to be similar for Collapsar BH-AD systems

MHD CC
Magnetic “towers”

Mosta et al 2014
Summary and conclusions

• Pulsar are prototypical relativistic accelerators.
• In the last 10 years our ability to model the structure of the pulsar/NS magnetosphere, and the properties of its FF outflows has been greatly enhanced
• There are still open questions regarding the way particles are extracted and accelerated in the inner magnetosphere.
• PWNe can be used to understand the interaction of a relativistic outflow with a confining environment, and the formation of relativistic bubbles
• There are still important open question on how non-thermal particles in those systems are accelerated.
• Pulsar wind theory is also at the base of the Millisecond magnetar model for GRBs.
Summary and conclusions

• Pulsar are prototypical relativistic accelerators.
• In the last 10 years our ability to model the structure of the pulsar/NS magnetosphere, and the properties of its FF outflows has been greatly enhanced.
• There are still open questions regarding the way particles are extracted and accelerated in the inner magnetosphere.
• PWNe can be used to understand the interaction of a relativistic outflow with a confining environment, and the formation of relativistic bubbles.
• There are still important open question on how non-thermal particles in those systems are accelerated.
• Pulsar wind theory is also at the base of the Millisecond magnetar model for GRBs.

Thank you