CRISTIAN GIOVANNY BERNAL

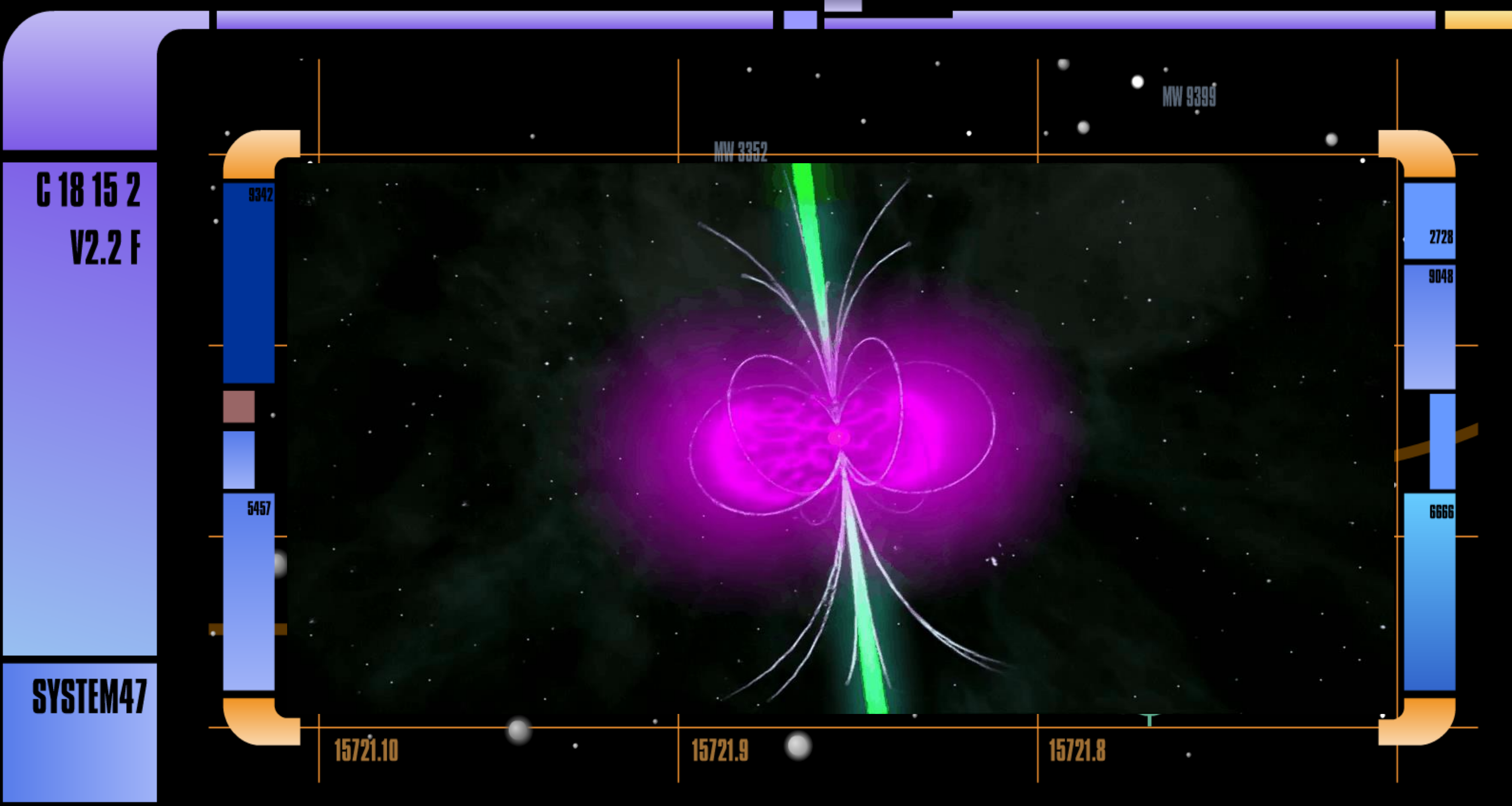
ASTROPHYSICS - COSMOLOGY - ASTROFLUIDS

UNAL - BOGOTÁ - COLOMBIA - 11.20.2024

547

THE NEUTRON STARS DIVERSITY

A MAGNETIC HISTORY



OUTLINE

CALIBRATE

STATUS

PRIMARY SEQUENCE

SECONDARY SEQUENCE

AUXILIARY SEQUENCE

EMERGENCY SEQUENCE

- THE NEUTRON STARS DISCOVERY
- THE ZOO OF NEUTRON STARS
- THE MAGNETIC FIELD EVOLUTION
- MAGNETARS & G.U.N.S.

MODE SELECT

ACCESS

THE NEUTRON STARS DISCOVERY

LCARS 23654

38-676783

In 1934, following James Chadwick's 1932 discovery of the neutron, Walter Baade and Fritz Zwicky proposed the existence of neutron stars. They suggested that supernovae result from the gravitational collapse of ordinary stars into extremely dense neutron stars.

INITIATE INT

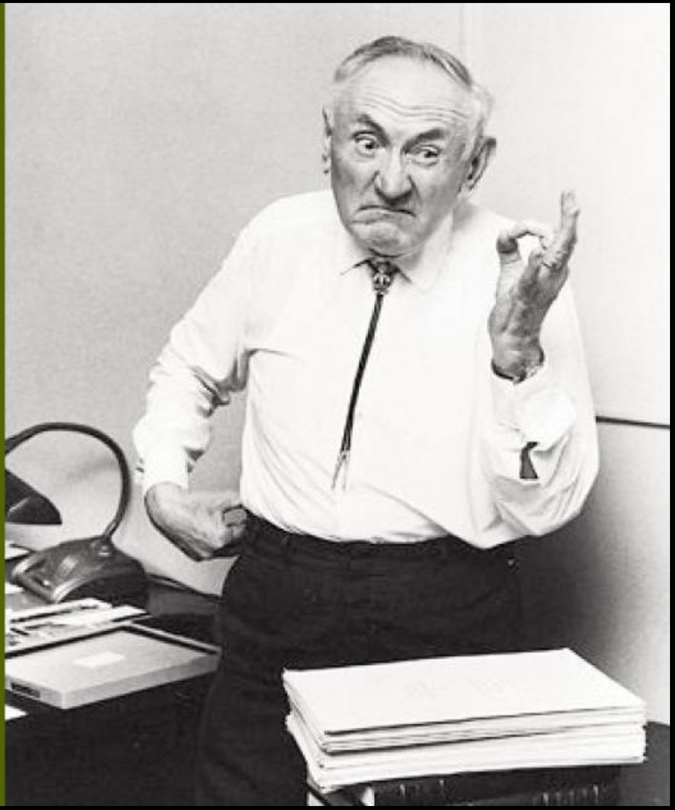
CALIBRATE EXT

04-56283

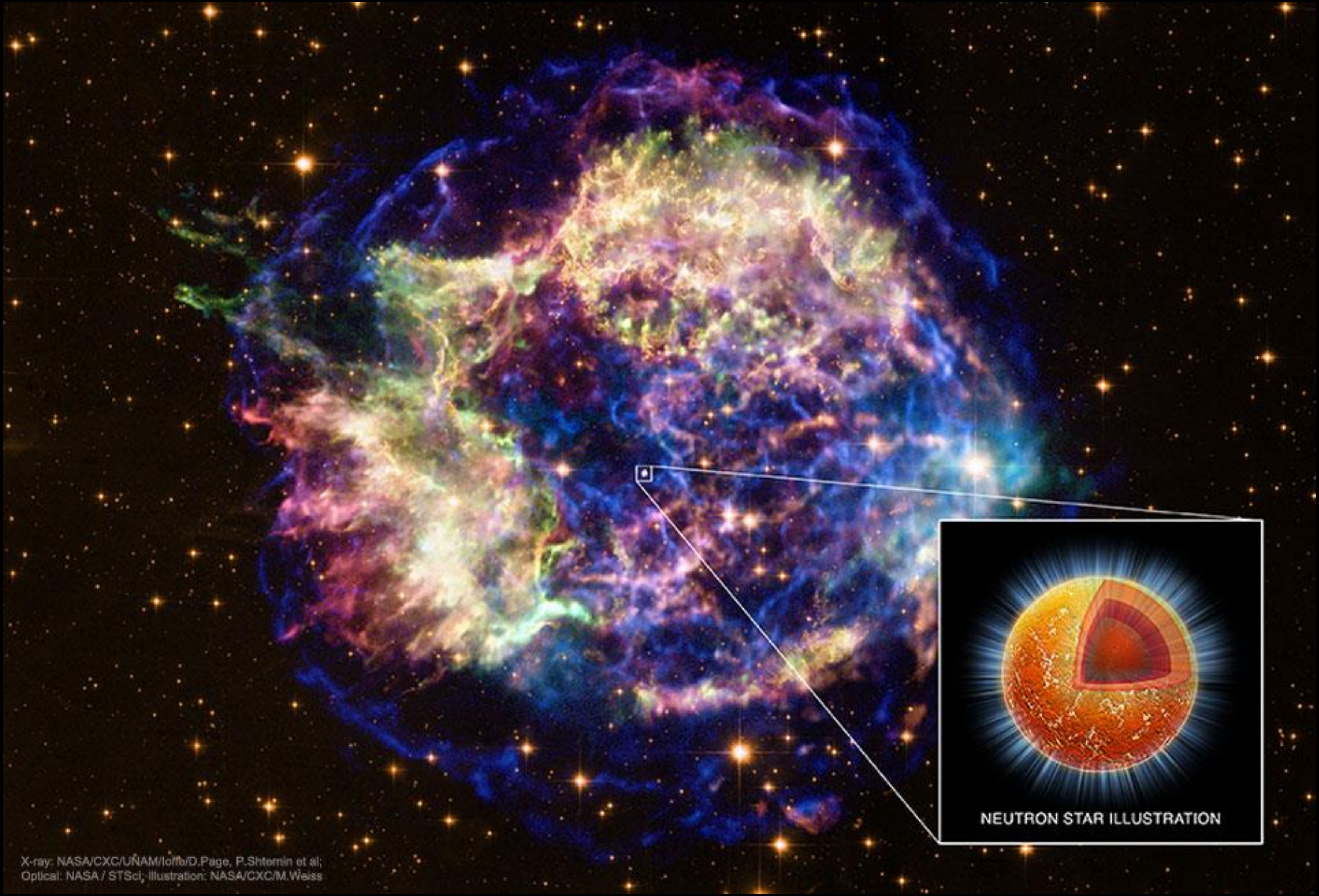
04-722834

42-588235

09-273475



THE Cas-A SUPERNOVA



THE NEUTRON STARS DISCOVERY

LCARS 46575

38-676783

In 1967, Jocelyn Bell Burnell, while analyzing radio telescope data at the University of Cambridge, detected regular radio pulses every 1.33 seconds. These signals identified as emanating from rapidly rotating neutron stars, now known as pulsars.

INITIATE INT

CALIBRATE EXT

04-56283

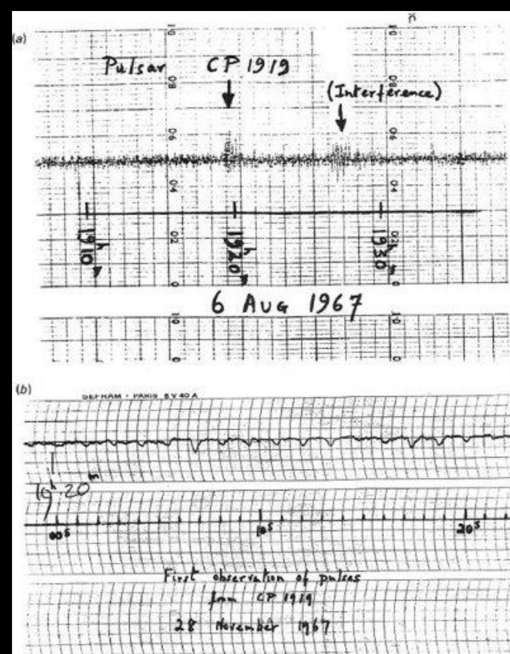
04-722834

42-588235

09-273475

10 20 30 40 50 60 70 80 90

PULSARS DISCOVERY



10 20 30 40 50 60 70

JOCELYN BELL BURNELL

Anthony Hewish received the Nobel Prize in 1974 for his explanation of pulsars. It is called the *"lighthouse model"*.

THE ZOO OF NEUTRON STARS

LCARS 52315

02-632427

Compact stars form the endpoint of stellar evolution. Our Galaxy is populated by billions of white dwarfs (some thousand), a few hundred million neutron stars (few thousand) and probably by a few hundred thousand black holes (few dozen).

SENSOR LOG | SPECIAL SENSOR EQUIPMENT | INT

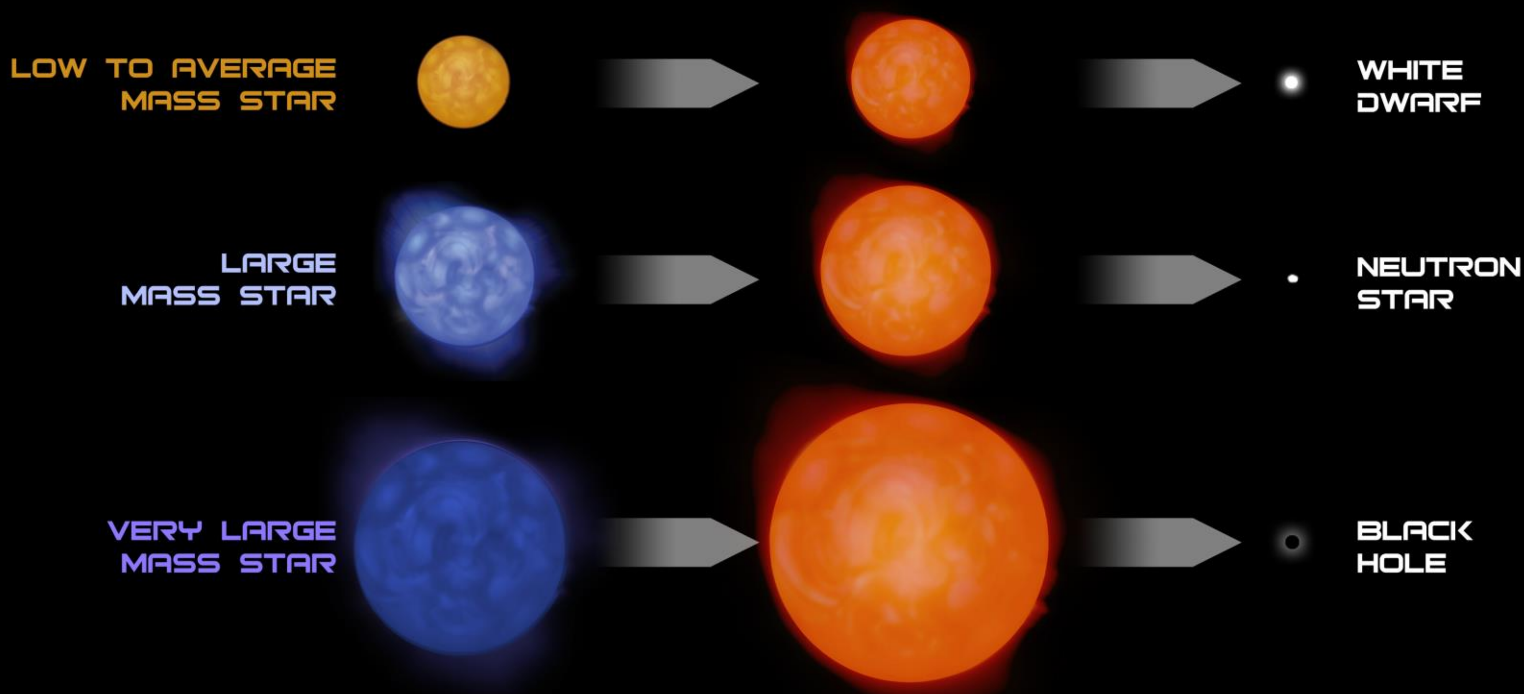
COURSE CORRECTIONS | EXT

24-689100

08-577125

41-963751

37-589348



The fate of a star depends on its mass (size not to scale)

THE ZOO OF NEUTRON STARS

LCARS 52315

02-632427

The discovery of RPP was the single most significant event responsible for the recognition of NSs as a physical reality. Allow the first calculation of their masses and radii. A dipolar oblique rotator model is proposed for the pulsar.

SENSOR LOG | SPECIAL SENSOR EQUIPMENT | INT

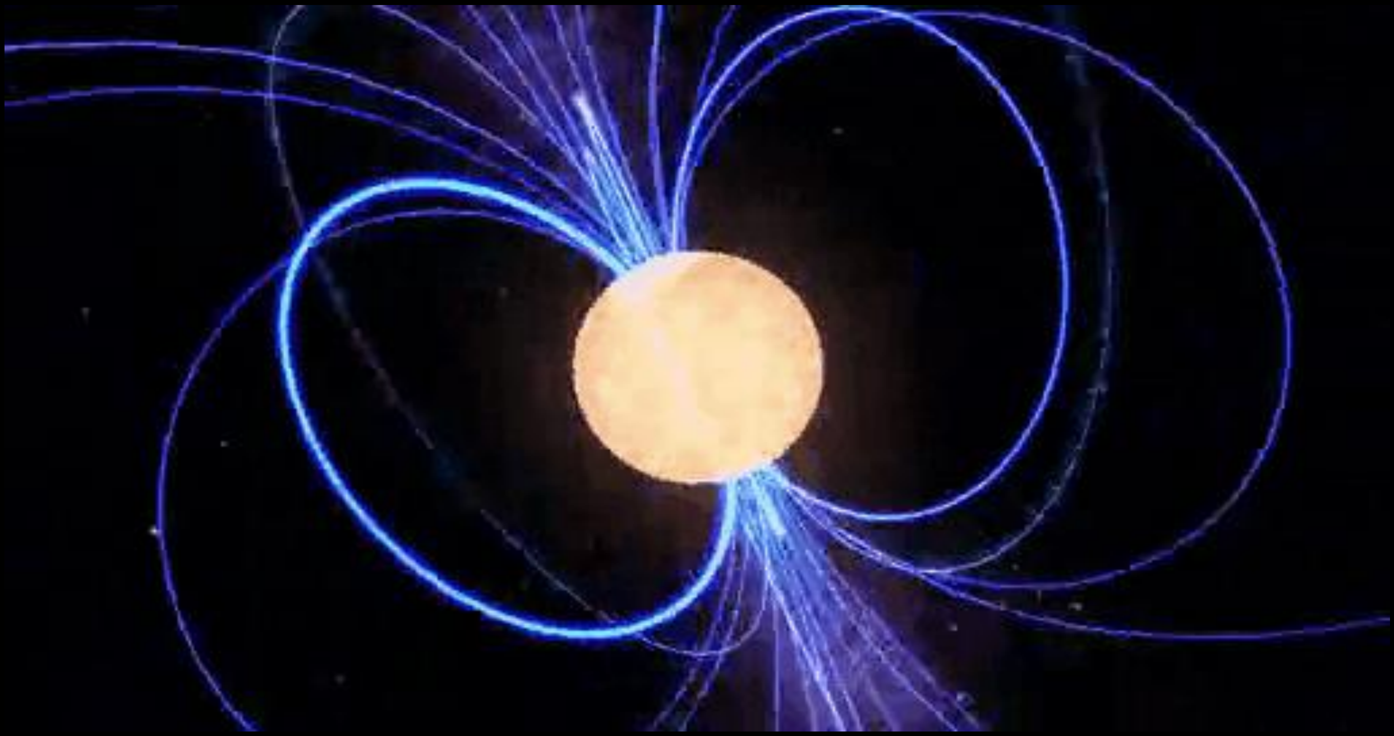
COURSE CORRECTIONS | EXT

24-689100

08-577125

41-963751

37-589348



ROTATION-POWERED PULSARS

THE ZOO OF NEUTRON STARS

LCARS 52315

02-632427

Giacconi (1962) search for extrasolar X-ray sources (Sco X-1, Cen X-3, Her X-1). About 50 cosmic X-ray sources were discovered, most of these were inside our Galaxy, but the first extragalactic X-ray source—the giant elliptical galaxy M87—was also discovered.

SENSOR LOG | SPECIAL SENSOR EQUIPMENT | INT

COURSE CORRECTIONS | EXT

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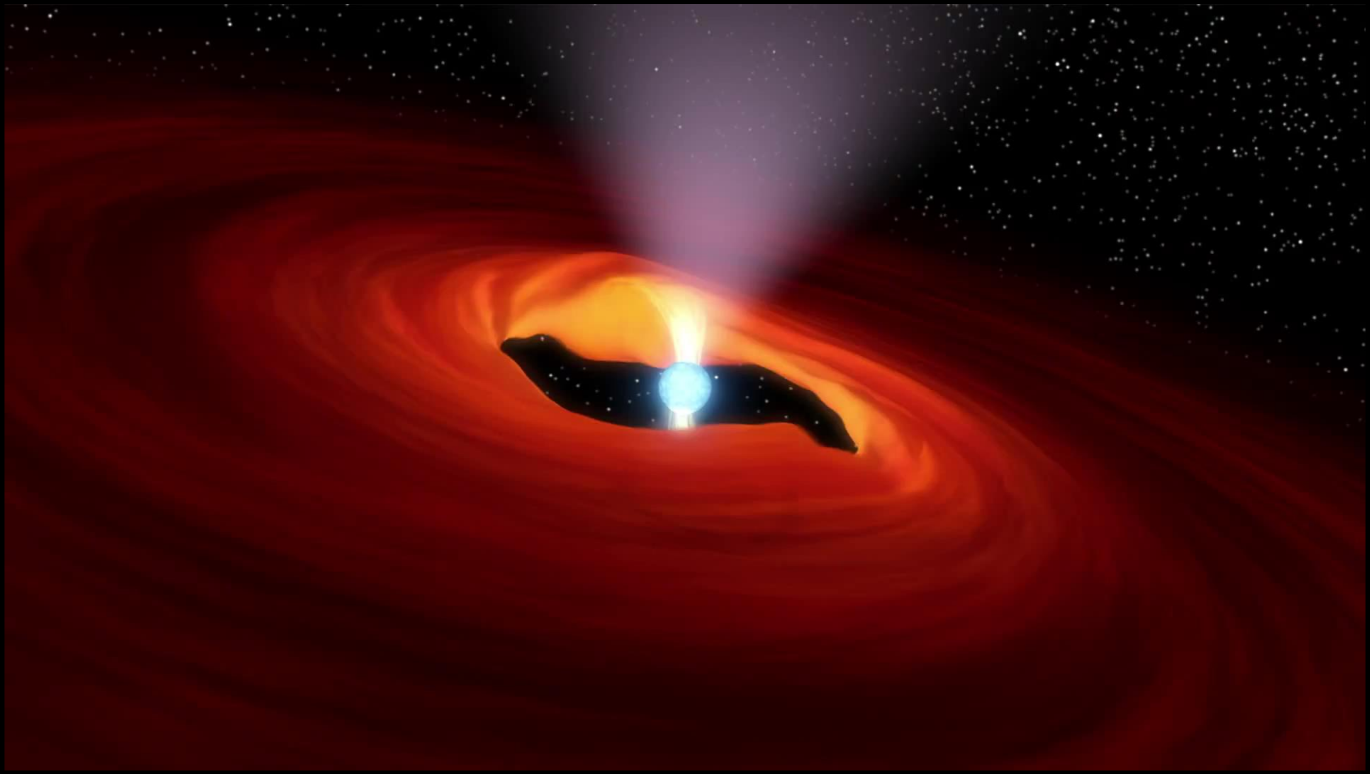
41-963751

37-589348



ACCRETION-POWERED PULSARS

THE ZOO OF NEUTRON STARS

LCARS 46575

38-676783

The last decades has shown us that the observational properties of neutron stars are remarkably diverse: from magnetars to rotating radio transients, from radio pulsars to isolated NSs, from central compact objects to millisecond pulsars.

INITIATE INT

CALIBRATE EXT

04-56283

04-722834

42-588235

09-273475

THE NEUTRON STAR DIVERSITY

10 20 30 40 50 60 70 80 90

10 20 30 40 50 60 70

PULSAR - PWN - SNR

THE ZOO OF NEUTRON STARS

LCARS 52315

02-632427

The Chandra era has seen the proliferation of a greater variety of distinct observational classes of neutron star than ever before. With emission spanning the electromagnetic spectrum and radiative properties that span a huge fraction of conceivable phase space.

SENSOR LOG | SPECIAL SENSOR EQUIPMENT | INT

COURSE CORRECTIONS | EXT

24-689100

08-577125

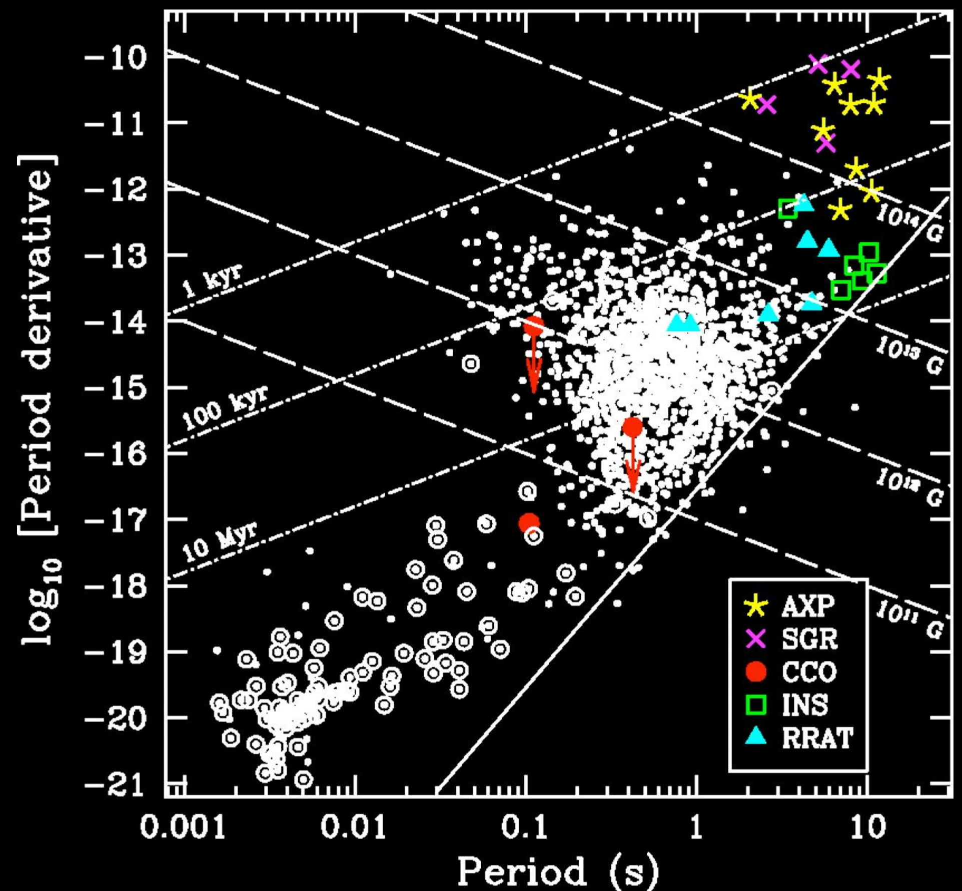
41-963751

37-589348

P-PDOT DIAGRAM

AXP	ANOMALOUS X-RAY PULSAR
SGR	SOFT-GAMMA REPEATER
CCO	CENTRAL COMPACT OBJECT
INS	ISOLATED NEUTRON STAR
RRAT	ROTATING RADIO TRANSIENT

Data from the Australian Telescope National Facility Pulsar Catalog: 1704 obects, including 1674 RPPs (small white dots), 9 AXPs (yellow crosses), 5 SGRs (pink crosses), 3 CCOs (red circles), 6 INSs (green squares), and 7 RRATs (blue triangles) for which these parameters have been measured. Open circles indicate binary systems.

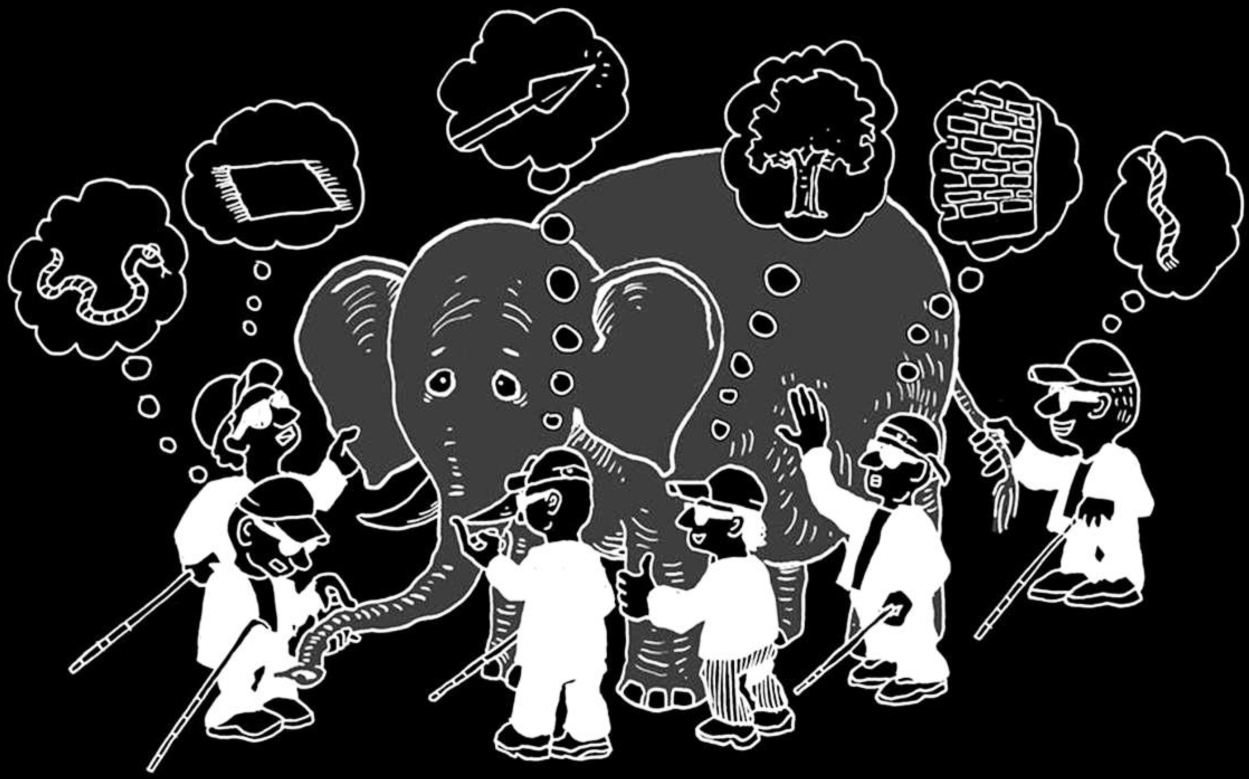


THE MAGNETIC FIELD EVOLUTION

Neutron stars prefer to radiate most of their energy at X-ray and gamma-ray wavelengths. But whether their emission is powered by rotation, accretion, heat, magnetic fields or nuclear reactions, they are all different species of the same animal.

C 18 15 2

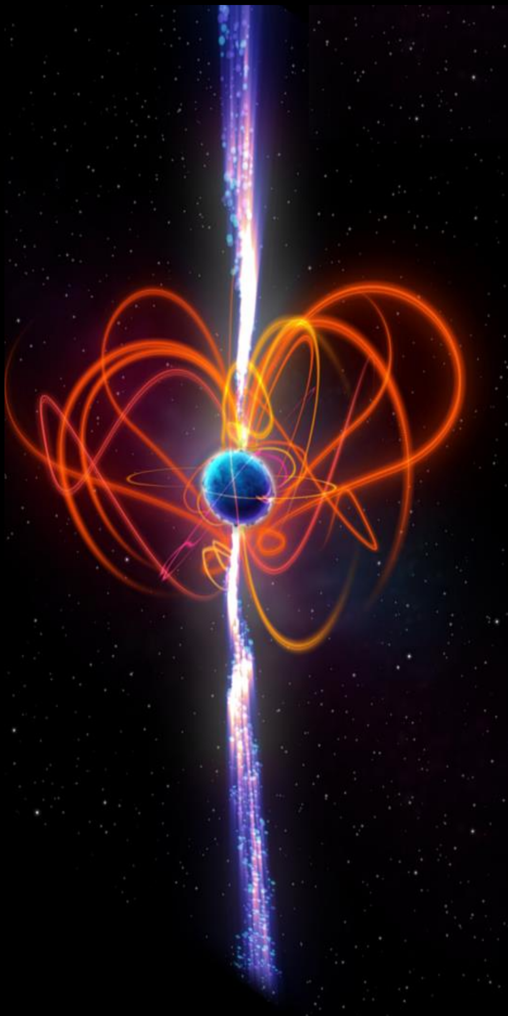
V2.2 F



SYSTEM47

DIFFERENT CHARACTERISTICS OF NEUTRON STARS

MAGNETIC



OMICRON 3854-4875 Y·52

THE FOSIL FIELD

In the 1960s, it was proposed that neutron stars' magnetic fields are amplified through flux conservation during the core collapse, as the progenitor's matter is significantly compressed.

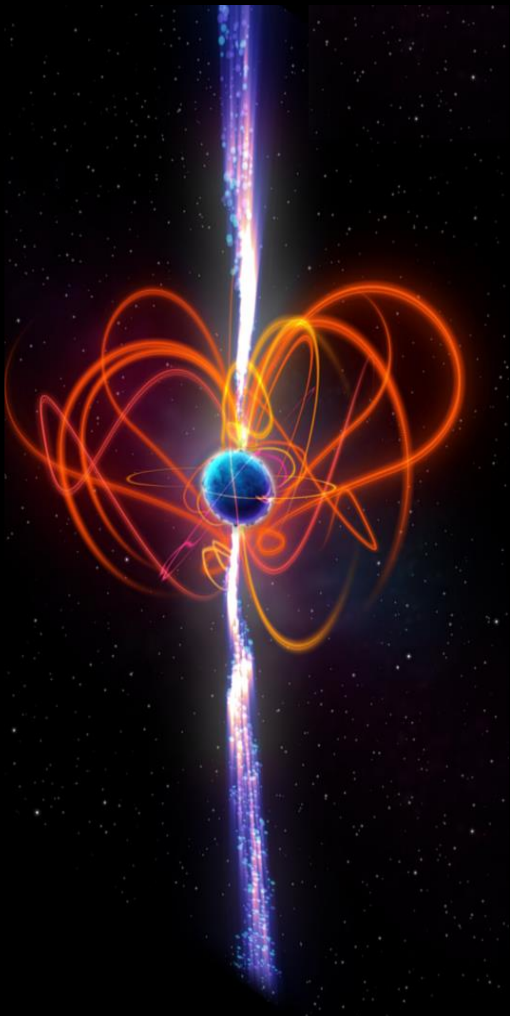
THERMOMAGNETIC EFFECTS

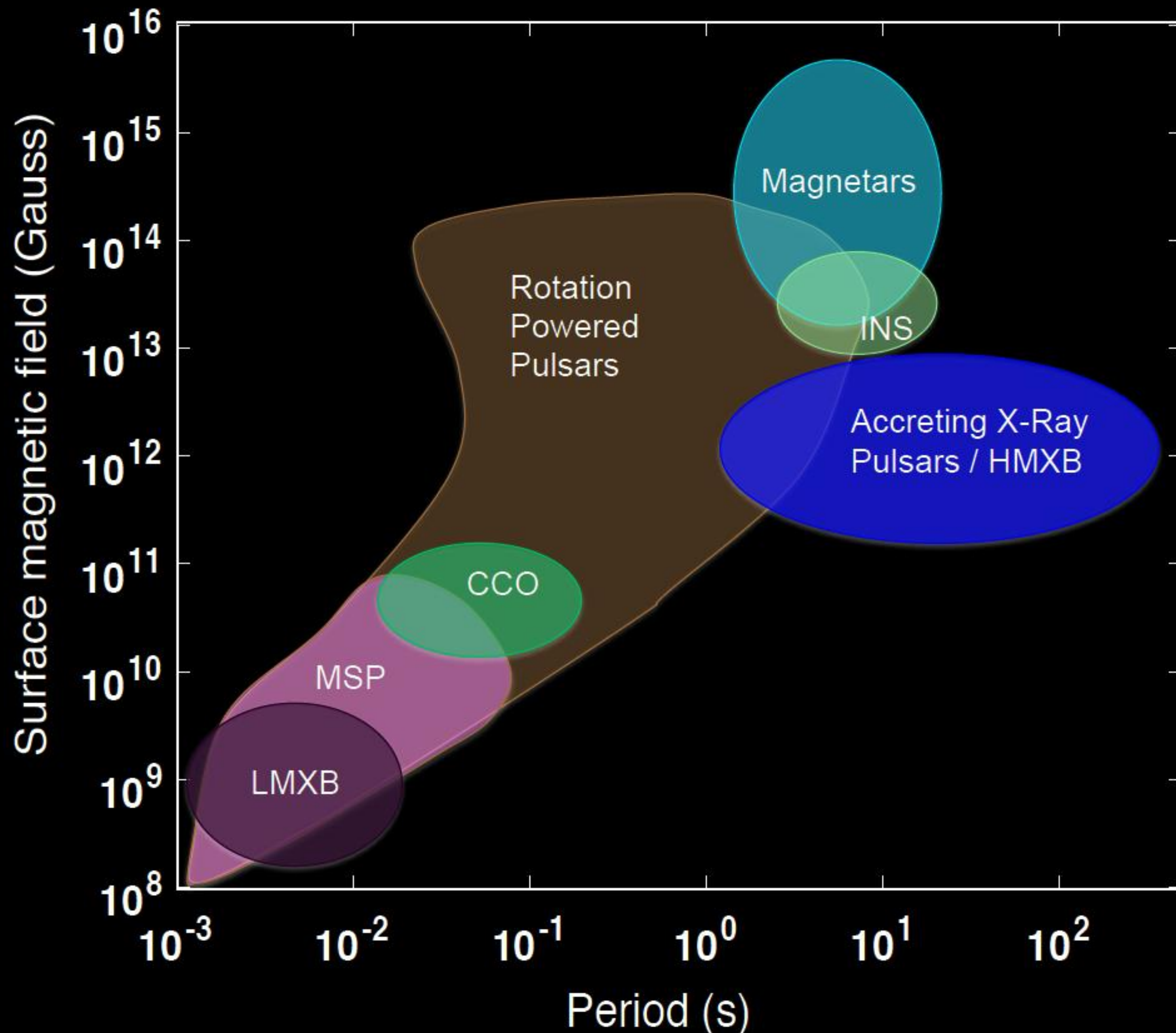
As neutron star collapse became understood, complications to the simple picture arose. Initially hot and fluid, the star cools to crust crystallization, where thermo-magnetic effects might enhance its magnetic field.

DYNAMO IN YOUNG NEUTRON STARS

In the early 1990s, Thompson and Duncan made the pioneering suggestion that convection-driven dynamos in young neutron stars could generate extremely strong magnetic fields of significant magnitude. The magnetar model become to literature.

MAGNETIC

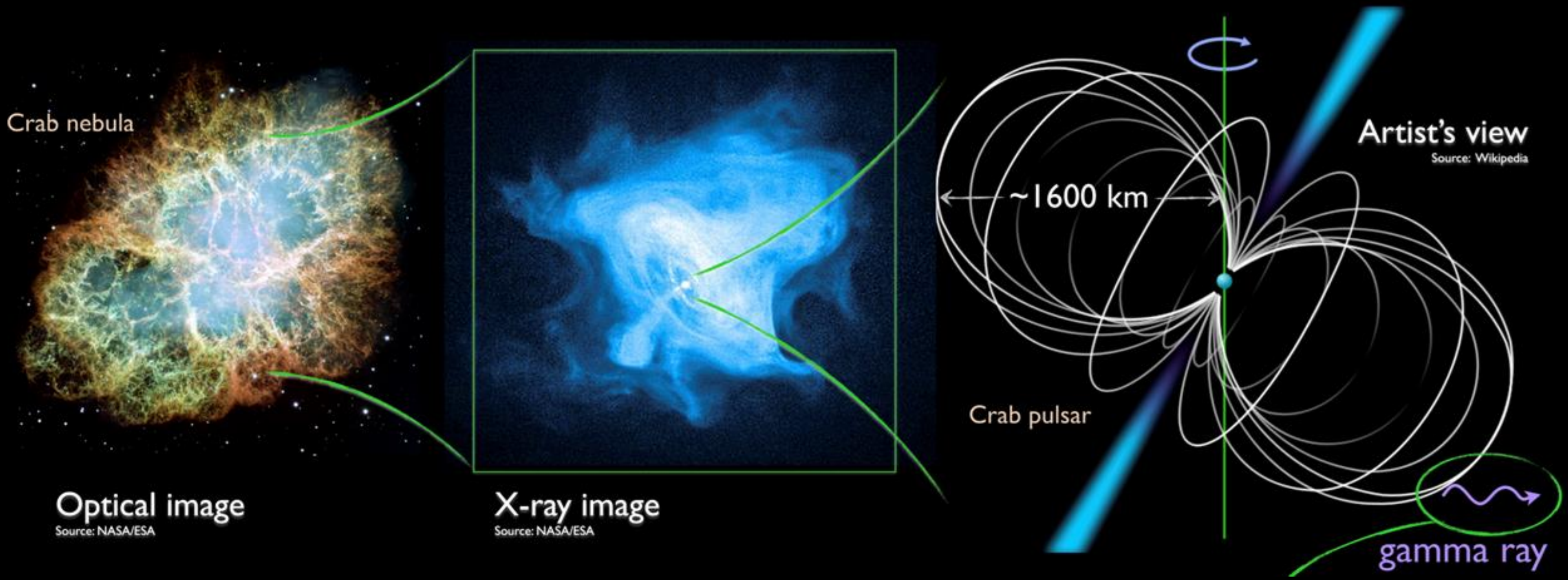




OMICRON 3854-4875 Y·52

THE MAGNETIC FIELD EVOLUTION

The origin of neutron star magnetic fields is still an unsolved problem. Few main mechanisms, a fossil field from the progenitor compressed during the core collapse and a proto-neutron star dynamo, are still competing to explain the large variety of observed field strengths.

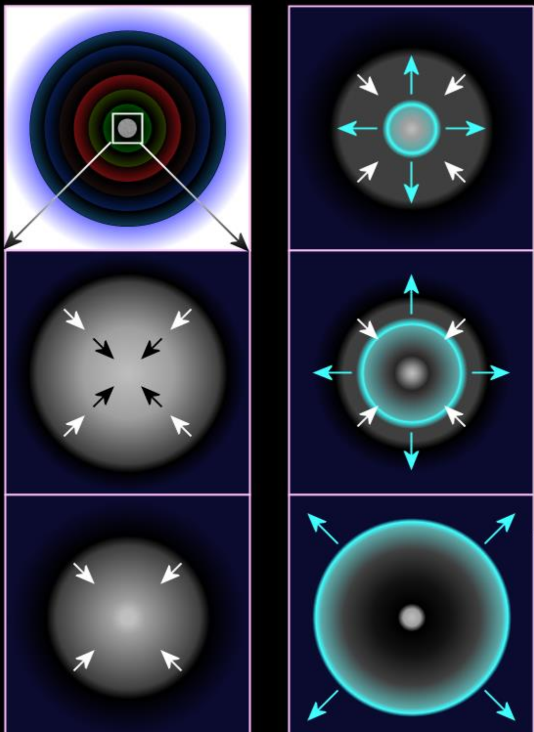


SUBMERGENCE AND REEMERGENCE OF MAGNETIC FIELD MODEL

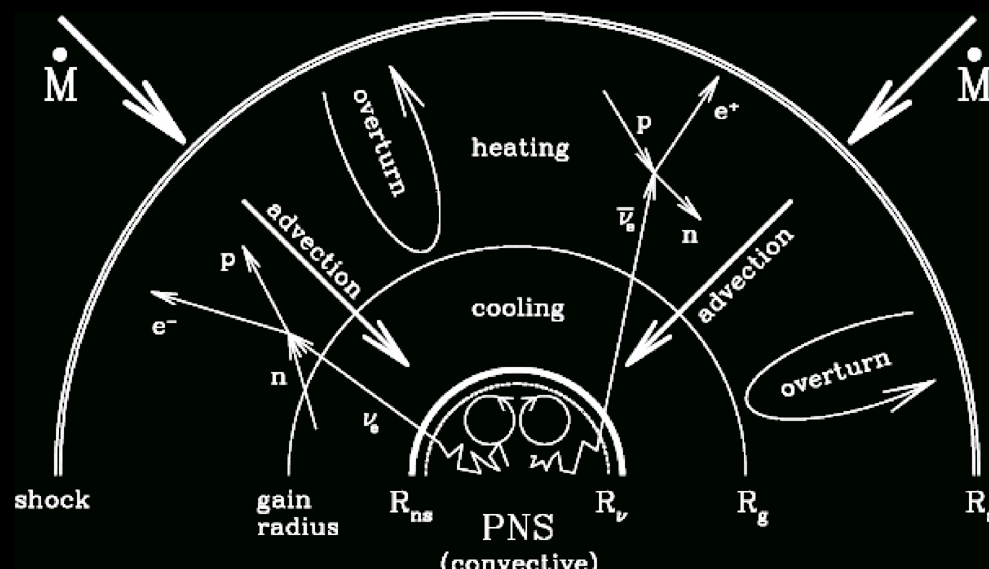
8889
C 18 15 2
V2.2 F
SYSTEM47

FALLBACK

72482 10 85 DELTA 9267 13
74558 3 88 BETA 50916 2
547



Depending on its strength and on how far out it was generated, this reverse shock can induce strong accretion onto the newborn neutron star on timescales of hours. This delayed accretion is different from the initial fallback that occurs seconds after the initial core collapse.



C 18 15 2
V2.2 F
70920 179 DELTA 831018 1
8896 42977
48730.23 5354 75332
76148.33 3959 72042

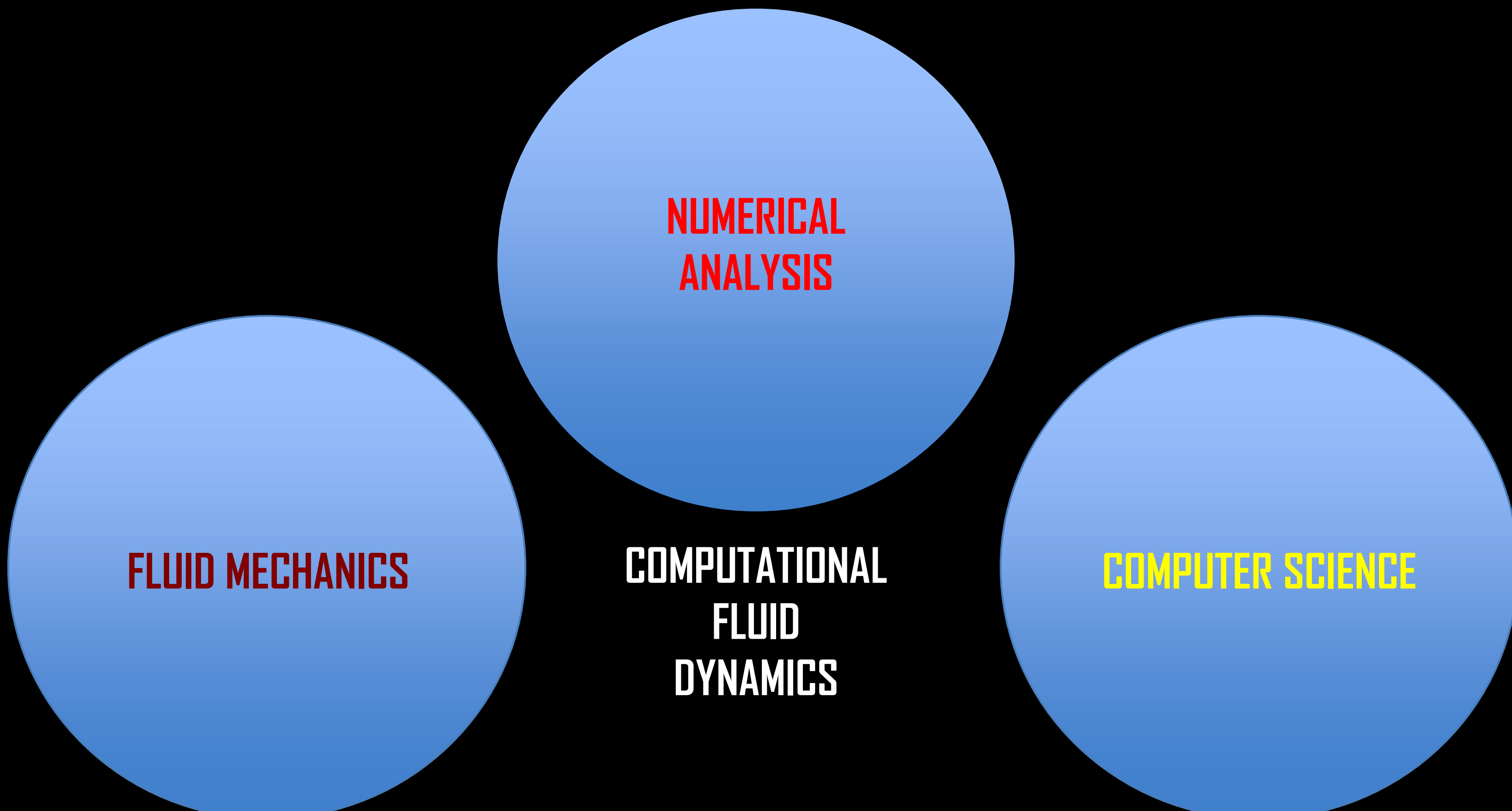
547

COMPUTATIONAL APPROACH

Simulation enables us to build a model of a system and allows us to do virtual experiments to understand how this system reacts to a range of conditions and assumptions. All simulation codes make approximations simply by making a choice of what equations are to be solved.

C 18 15 2

V2.2 F



SYSTEM47

THE FLASH CODE V4.8

The Flash Center for Computational Science is the home of FLASH, a publicly available multiphysics multiscale simulation code. Research projects include high-energy density physics, thermonuclear-powered supernovae and fluid-structure interactions.

THE FLASH CENTER

DIRECTOR GROUP LEAD
PETROS TZEFERACOS

CODE GROUP LEAD
ADAM REYES

SCIENTIFIC DATA ANALYSIS
MIKE PAPKA

- HYDRODYNAMICS: UNSPLIT PPM AND WENO; SPLIT PPM; 2T + RADIATION
- MAGNETOHYDRODYNAMICS: UNSPLIT STAGGERED MESH; SPLIT 8 WAVE
- EQUATION OF STATE: IDEAL GAS; DEGENERATE PLASMA; MULTIMATERIAL
- RADIATION TRANSFER: MULTIGROUP FLUX-LIMITED DIFFUSION
- DIFFUSION AND CONDUCTION: IMPLICIT WITH AMR
- LASER ENERGY DEPOSITION: GEOMETRIC OPTICS WITH INVERSE BRENSSTRAHLUNG
- HEDP: CORE-COLLAPSE PHYSICS
- OPACITY: CONSTANT; MULTIMATERIAL TABULAR
- PARTICLES: TRACER; MASSIVE; SINK; CHARGED
- GRAVITY: CONSTANT; POINTMASS; PLANAR; SELF GRAVITY
- NUCLEAR BURNING SEVERAL NETWORK
- COSMOLOGY LCDM COSMOLOGICAL FLUID MODEL
- MAGNETIC RESISTIVITY, CONDUCTIVITY
- PRIMORDIAL CHEMISTRY

PHYSICS SOLVERS

THE PHYSICS INPUT

A new FLASH problem is created by making a new directory in the FLASH setups directory. Every simulation directory contains routines to initialize the FLASH grid. The files that are usually included in the Simulation directory for a problem are:
Config, Makefile, Simulation_data.F90, Simulation_init.F90, Simulation_initBlock.F90, flash.par, Simulation_initSpecies.F90, Grid_bcApplyToRegionSpecialized, IO_writeIntegralQuantities.

$$
\begin{aligned}
\frac{\partial \rho}{\partial t} + \boldsymbol{\nabla}\cdot(\rho \mathbf{v}) &= 0,\\
\frac{\partial \rho \mathbf{v}}{\partial t} + \boldsymbol{\nabla}\cdot(\rho \mathbf{v}\mathbf{v} - \mathbf{B}\mathbf{B}) + \nabla P_* &= \rho \mathbf{g} + \boldsymbol{\nabla}\cdot\boldsymbol{\tau},\\
\frac{\partial \rho E}{\partial t} + \boldsymbol{\nabla}\cdot\left[\mathbf{v}\left(\rho E + P_*\right) - \mathbf{B}\left(\mathbf{v}\cdot\mathbf{B}\right)\right] &= \rho \mathbf{v}\cdot\mathbf{g} + O(\boldsymbol{\tau},\eta),\\
\boldsymbol{\nabla}\cdot(\mathbf{v}\cdot\boldsymbol{\tau} + \sigma\nabla T) + \boldsymbol{\nabla}\cdot(\mathbf{B}\times(\eta\boldsymbol{\nabla}\times\mathbf{B})) &= O(\boldsymbol{\tau},\eta),\\
\frac{\partial \mathbf{B}}{dt} + \boldsymbol{\nabla}\cdot(\mathbf{v}\mathbf{B} - \mathbf{B}\mathbf{v}) &= -\boldsymbol{\nabla}\times(\eta\boldsymbol{\nabla}\times\mathbf{B}).
\end{aligned}
$$

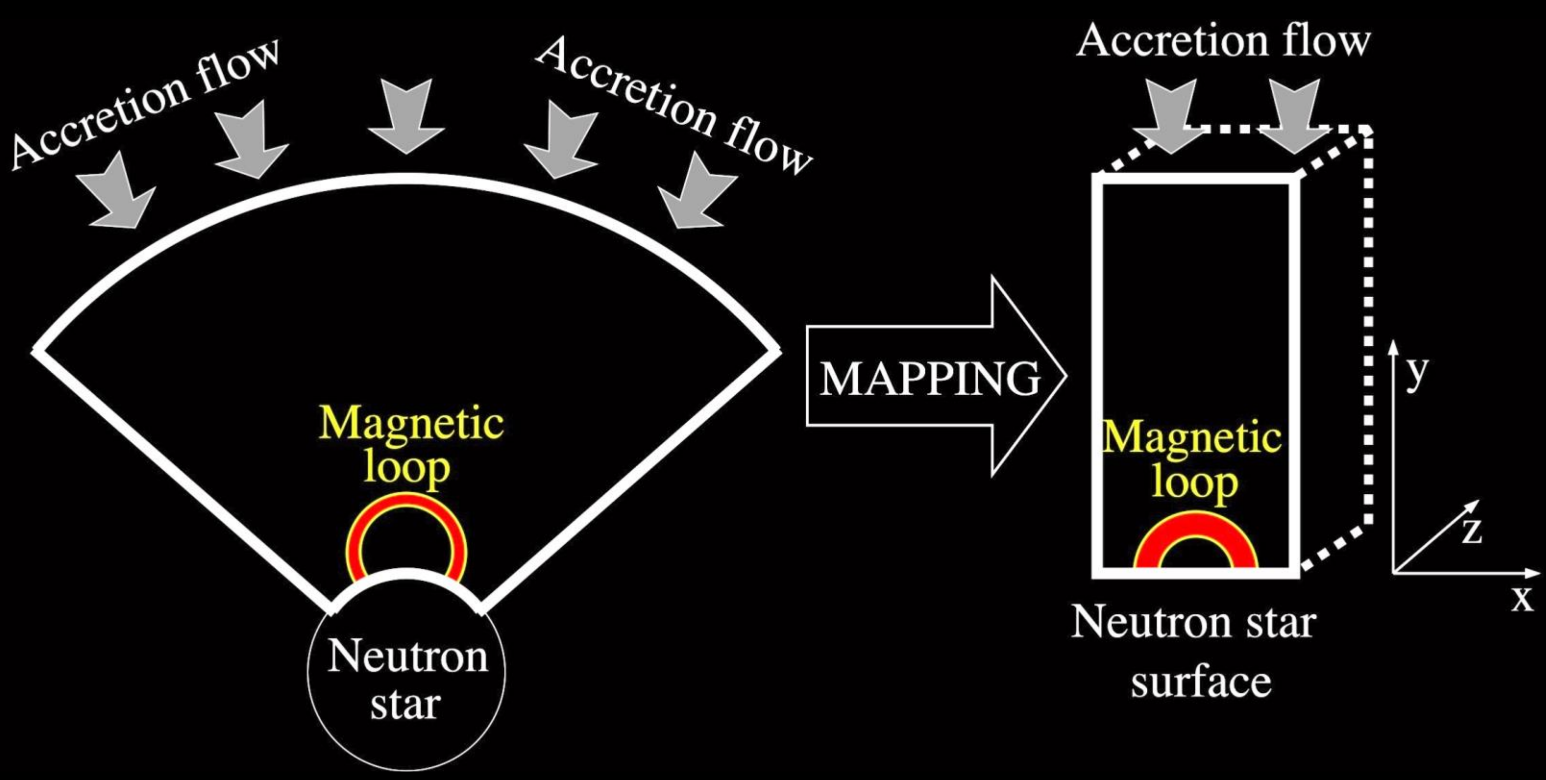
$$
\begin{aligned}
P_* &= P + \frac{B^2}{2},\\
E &= \frac{1}{2}v^2 + \varepsilon + \frac{B^2}{2\rho},\\
\boldsymbol{\tau} &= \mu\left[(\nabla\mathbf{v}) + (\nabla\mathbf{v})^{\mathrm{T}} - \frac{2}{3}(\nabla\mathbf{v})\right].
\end{aligned}
$$

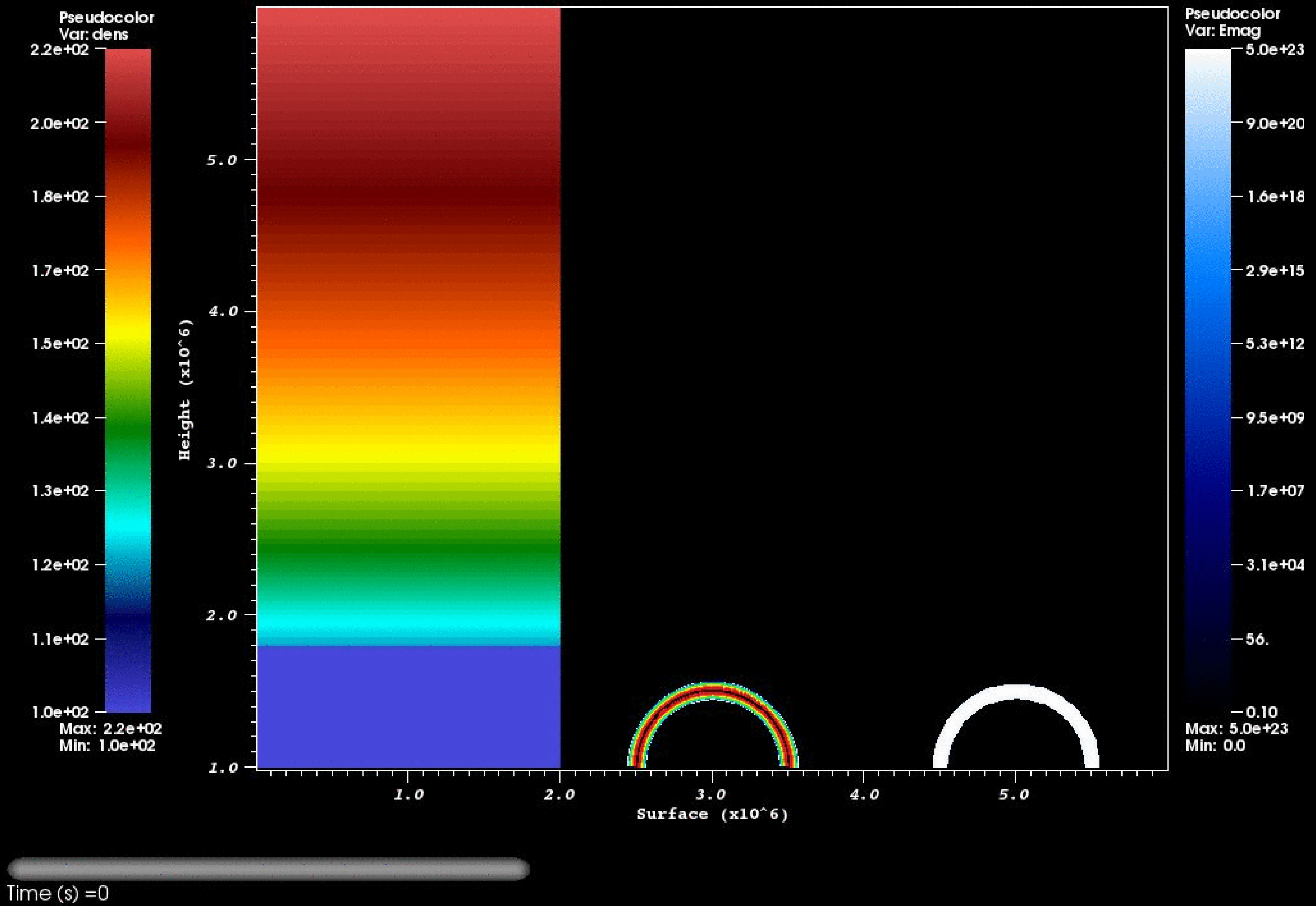
MAGNETOHYDRODYNAMIC EQUATIONS

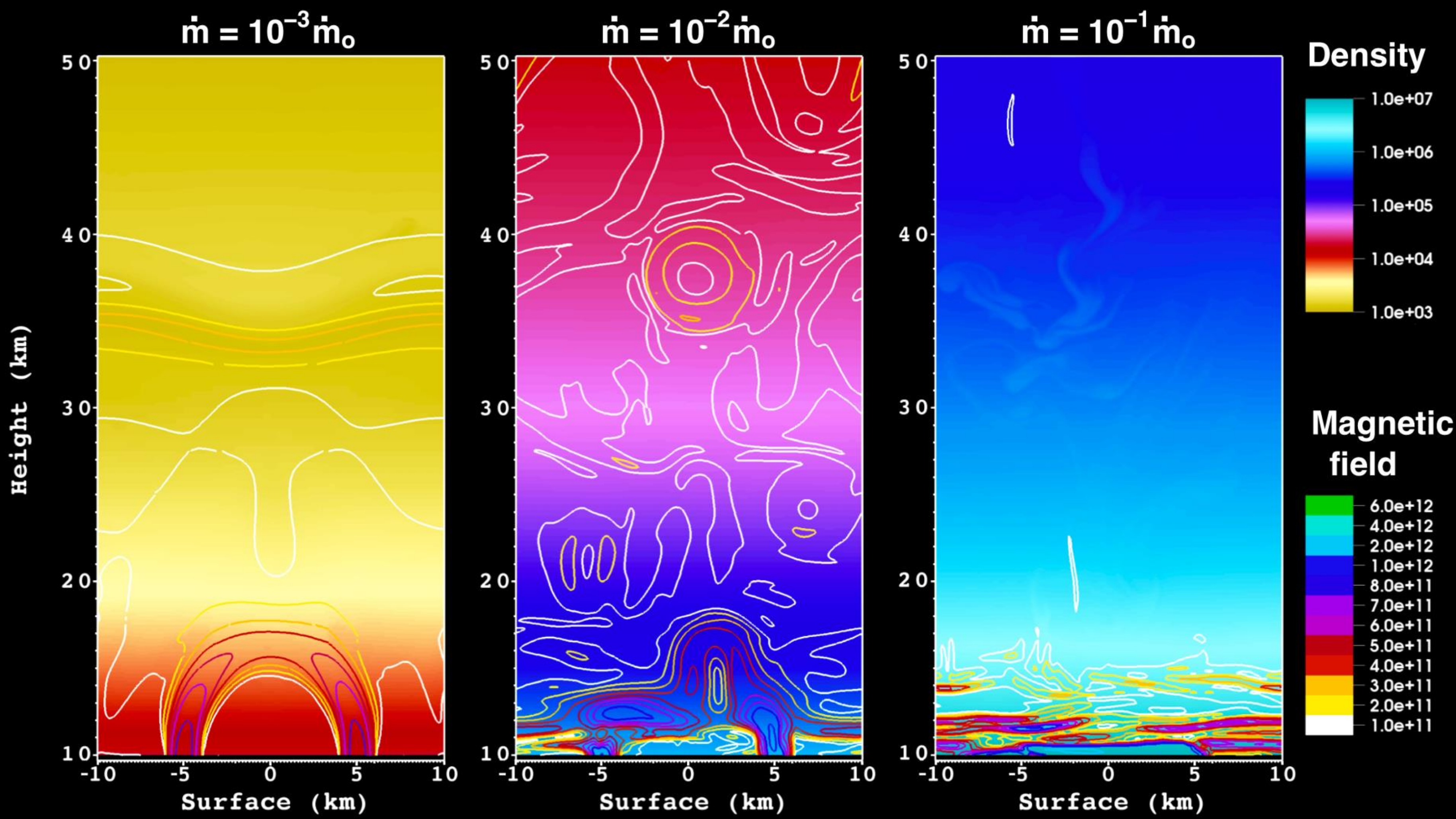
LCARS ACCESS
02-74656
05-80102
06-1701E
03-74205
04-78105
SCAN
NAVIGATION

ASTROPHYSICAL SIMULATIONS

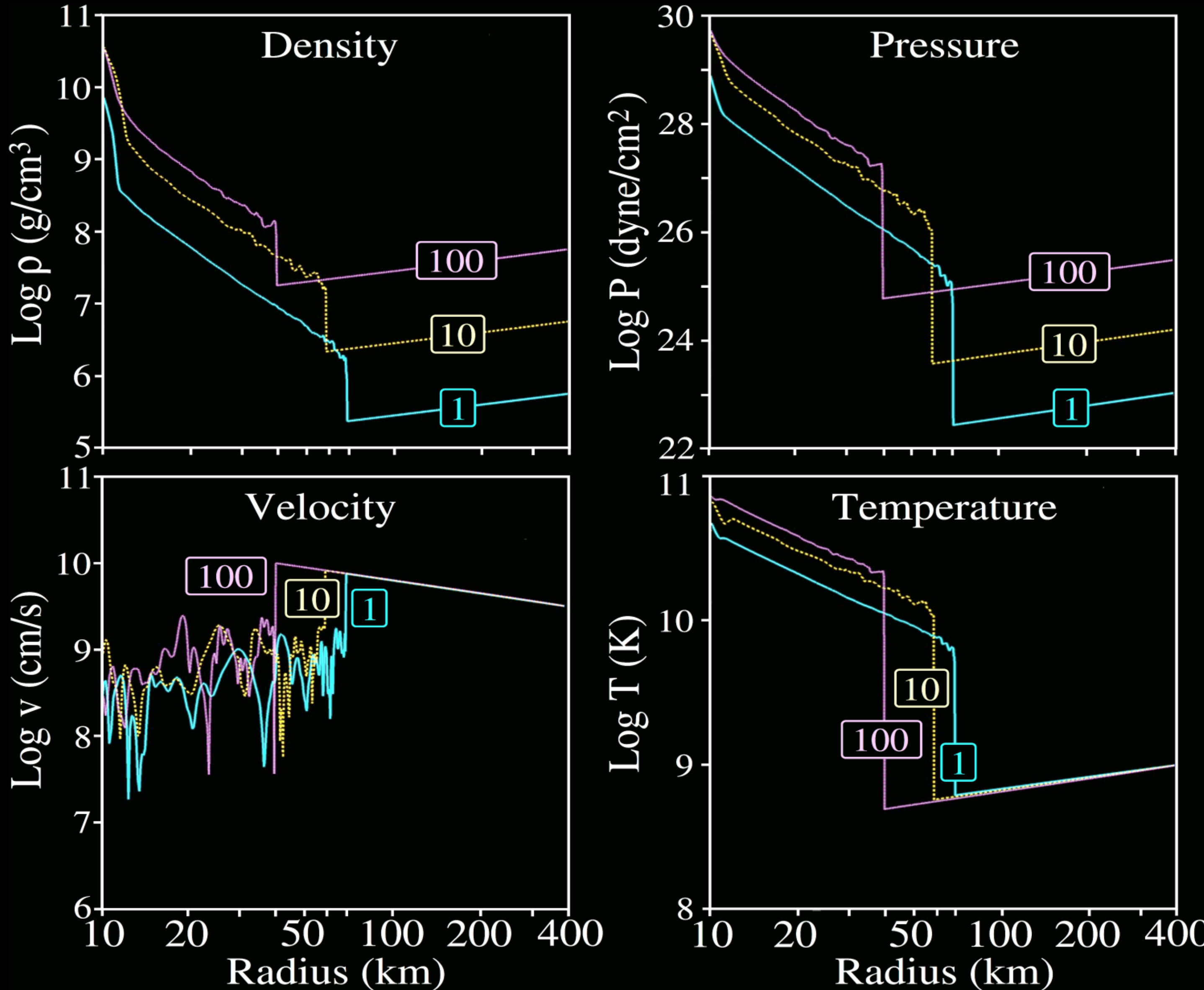
We consider as magnetic initial condition a magnetic field loop, in the shape of an hemi-torus. All the parameters are re-scaled from spherical symmetry to Cartesian symmetry. We use a customized version of FLASH to solve the whole set of ideal MHD equations.

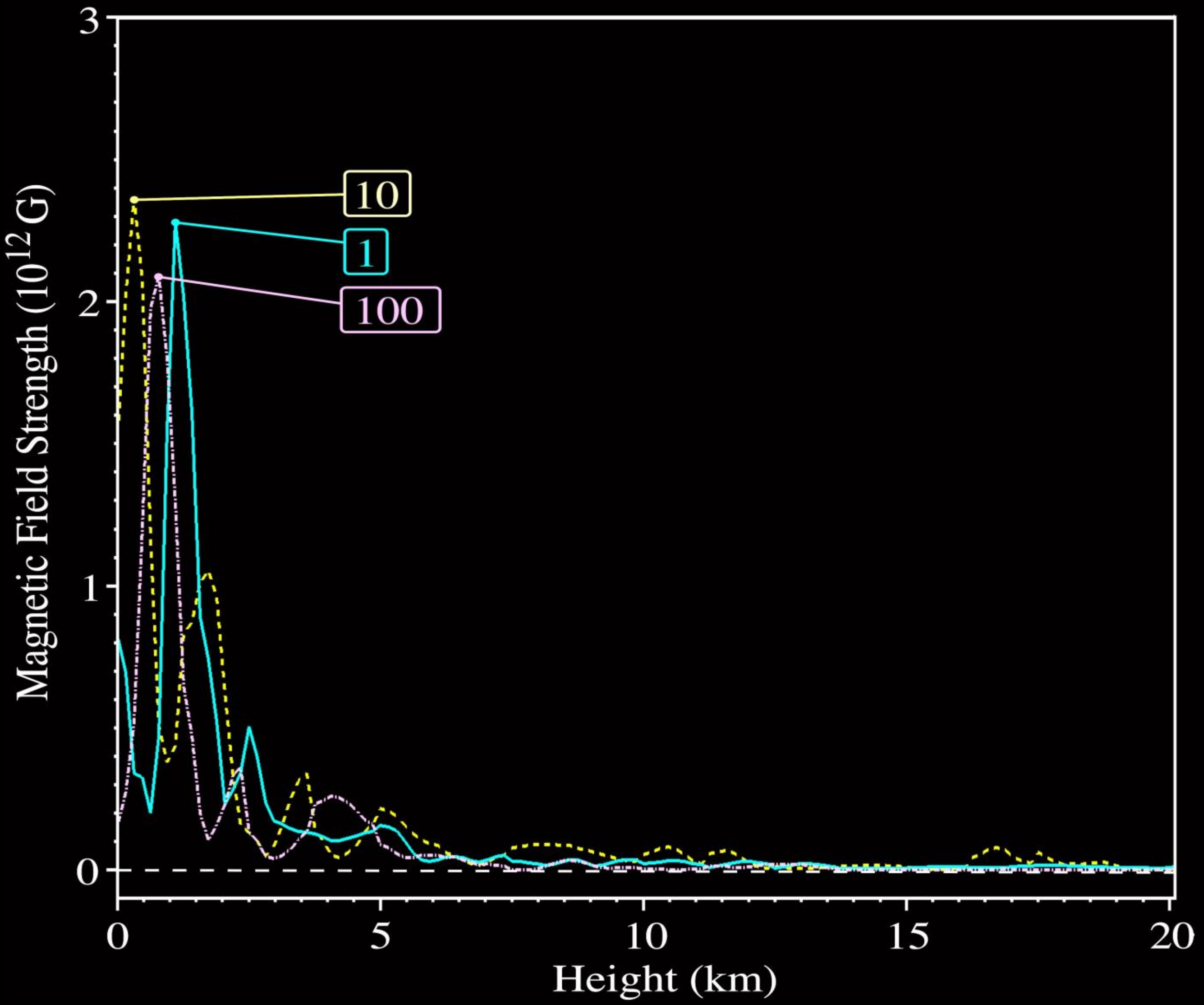



Pseudocolor
Var: dens
2.2e+02
2.0e+02
1.8e+02
1.7e+02
1.5e+02
1.4e+02
1.3e+02
1.2e+02
1.1e+02
1.0e+02
Max: 2.2e+02
Min: 1.0e+02
5.0
4.0
3.0
2.0
1.0
Height (x10^6)
1.0
2.0
3.0
4.0
5.0
Surface (x10^6)
Pseudocolor
Var: Emag
5.0e+23
9.0e+20
1.6e+18
2.9e+15
5.3e+12
9.5e+09
1.7e+07
3.1e+04
56.
0.10
Max: 5.0e+23
Min: 0.0
Time (s) =0



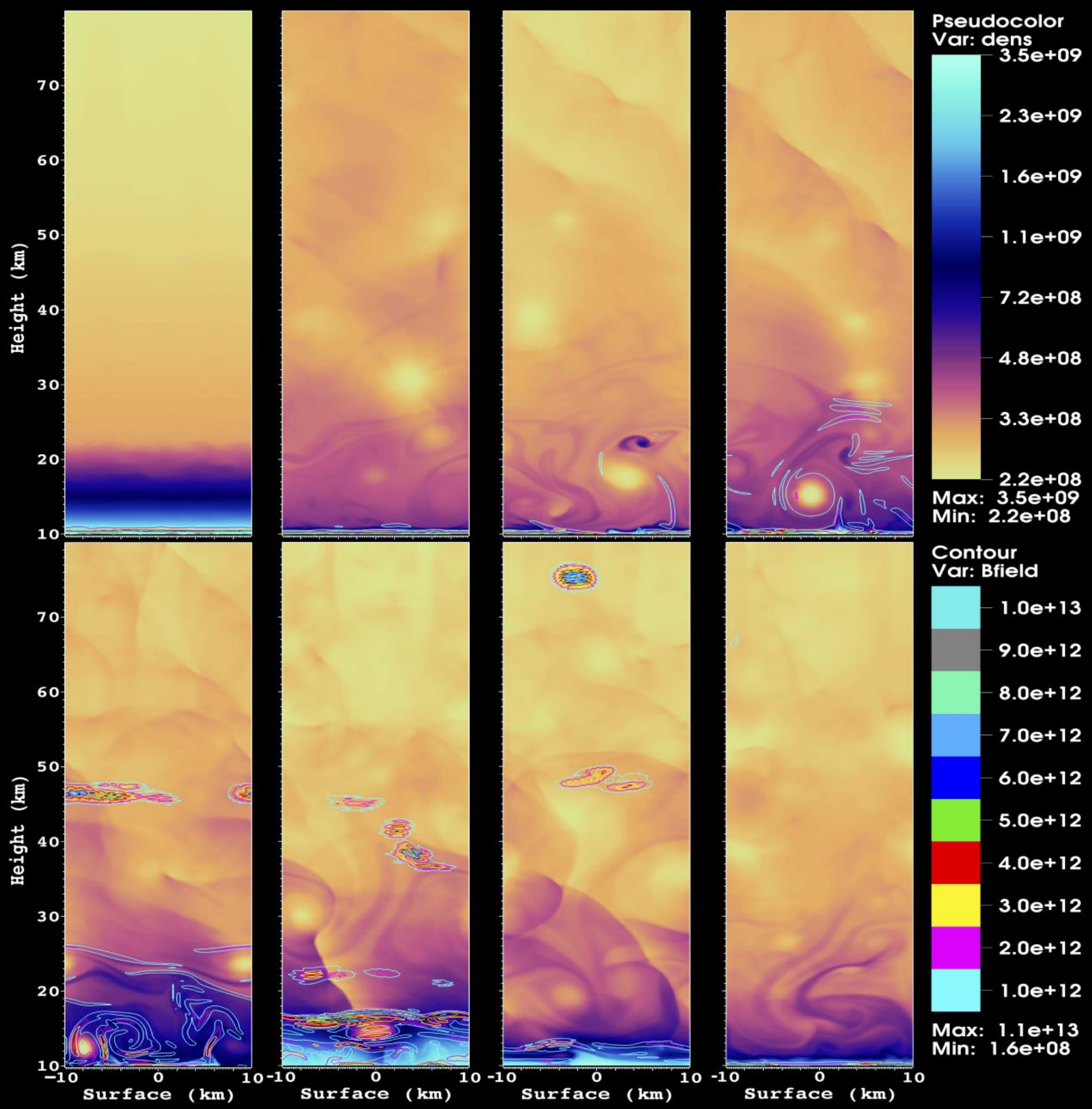
DEEP SUBMERGENCE OF MAGNETIC FIELD


Density
Log ρ (g/cm³)
11
10
9
8
7
6
5
100
10
1
Pressure
Log P (dyne/cm²)
30
28
26
24
22
100
10
1
Velocity
Log v (cm/s)
11
10
9
8
7
6
100
10
1
Temperature
Log T (K)
11
10
9
8
10
100
1
10
20
50
100
200
400
Radius (km)
10
20
50
100
200
400
Radius (km)



RADIAL MAGNETIC FIELD PROFILES

LCARS VIEW



MAGNETOHYDRODYNAMIC INSTABILITIES

Identification of pulsars with rotating NSs led to torrential theoretical work. This kind of pulsars, in which the rotation of the neutron star is responsible for the observed luminosity, are known as Rotation-Powered Pulsars (RPP). A dipolar oblique rotator model is proposed for the pulsar.

$$\dot{\Omega} = -k\Omega^n, \quad k = \frac{2m^2 \sin^2 \alpha}{3Ic^3}.$$

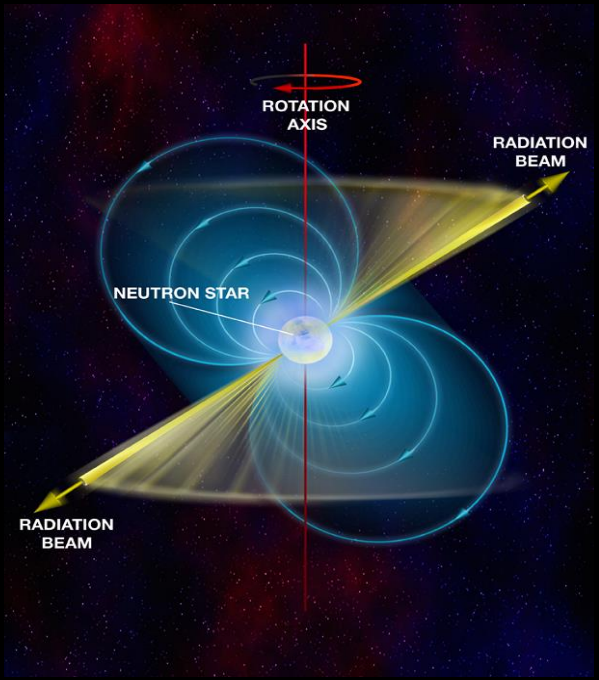
$$\tau = \frac{P}{(n-1)\dot{P}} \left[1 - \left(\frac{P_0}{P} \right)^{n-1} \right]$$

$$\dot{E} = \dot{E}_0 \left(1 + \frac{t}{\tau_0} \right)^{-\frac{(n+1)}{(n-1)}}$$

$$P = P_0 \left(1 + \frac{t}{\tau_0} \right)^{\frac{1}{n-1}}$$

$$n = \Omega \ddot{\Omega} / \dot{\Omega}^2 = 2 - P\ddot{P}/\dot{P}^2.$$

THE CANONICAL MODEL



THE OBLIQUE ROTATOR MODEL

LCARS ACCESS
02-1701E
03-74656

REEMERGENCE OF THE MAGNETIC FIELD MODEL

An alternative approach is to replace the constant *k* in the canonical model by a function of time *k*(*t*), and then to attempt to constrain it with the observations. A reasonable argument to propose such solution is the absence of the synchrotron nebula for these NSs.

04-74205 04-74205

04-74205
05-80102
06-78105
07-1701A
08-54215
09-25896
10-25874
PLASMA STABILITY

$$\dot{\Omega} = -k(t)\Omega^n, \quad k(t) = kf(t)$$

$$\tau = \frac{1}{f(t)}\left[\tau_0 + \int_0^t f(t)dt\right]$$

$$n = n_* + \frac{\dot{f}(t)}{f(t)}\frac{\Omega}{\dot{\Omega}} = n_* - \frac{\dot{f}(t)}{f(t)}\frac{P}{\dot{P}}$$

$$\dot{E} = \dot{E}_0 f(t)\left[\frac{\tau}{\tau_0}f(t)\right]^{-\frac{(n+1)}{(n-1)}}$$

$$P = P_0\left[\frac{\tau}{\tau_0}f(t)\right]^{\frac{1}{n-1}}$$

$$f(t) = \epsilon + \left[1 - \exp\left(-\frac{t}{\tau_B}\right)\right]$$

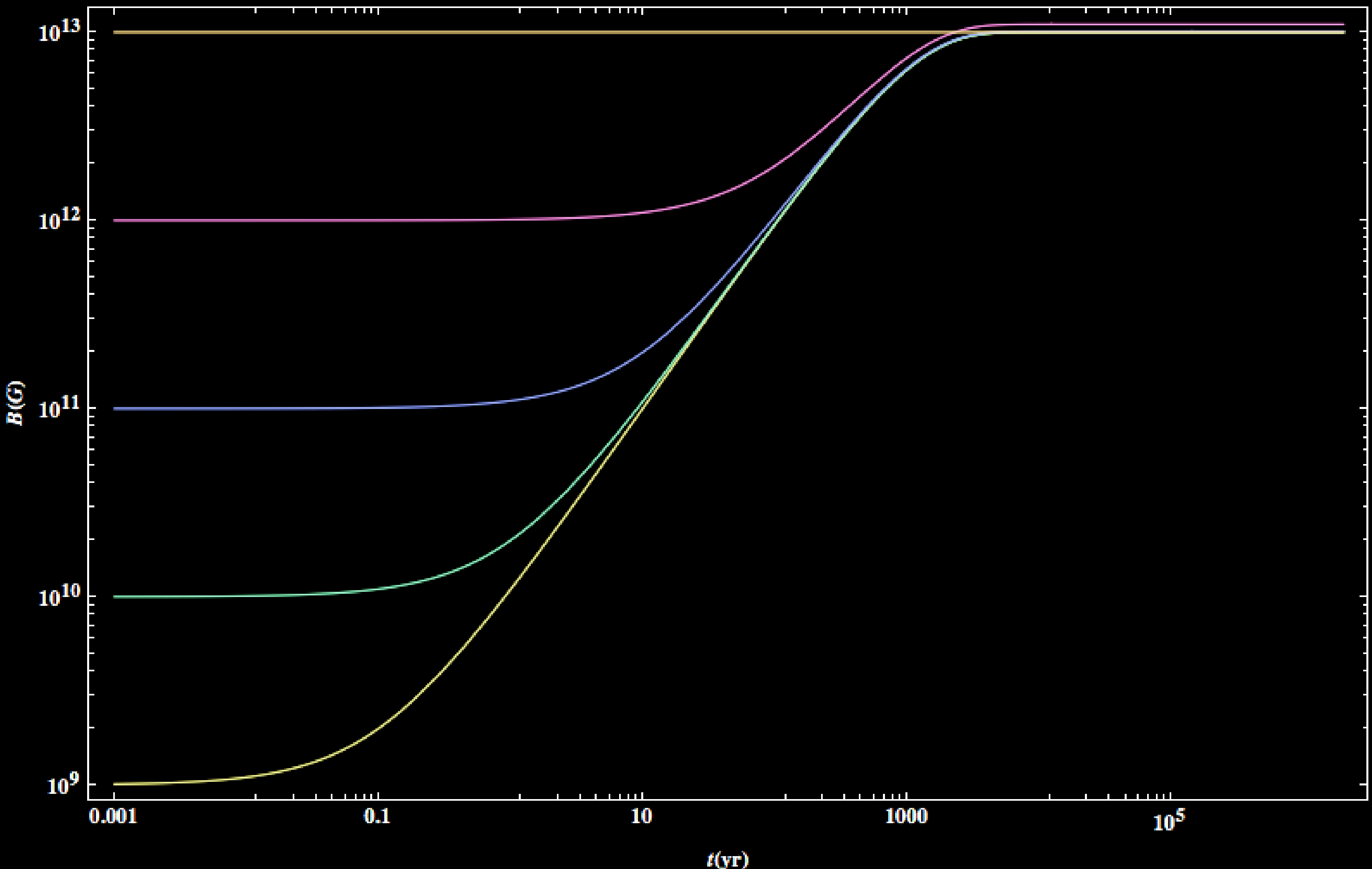
$$\tau = \frac{\tau_B(\epsilon - f(t)) + t(1-\epsilon) + \tau_0}{f(t)}$$

$$n = n_* - \frac{\exp\left(-\frac{t}{\tau_B}\right)}{\tau_B f(t)}\frac{P}{\dot{P}}$$

$$E = \frac{1}{2}I\Omega^2 = \frac{\dot{E}}{2}\frac{\Omega}{\dot{\Omega}} = \frac{(n-1)}{2}\tau\dot{E}$$

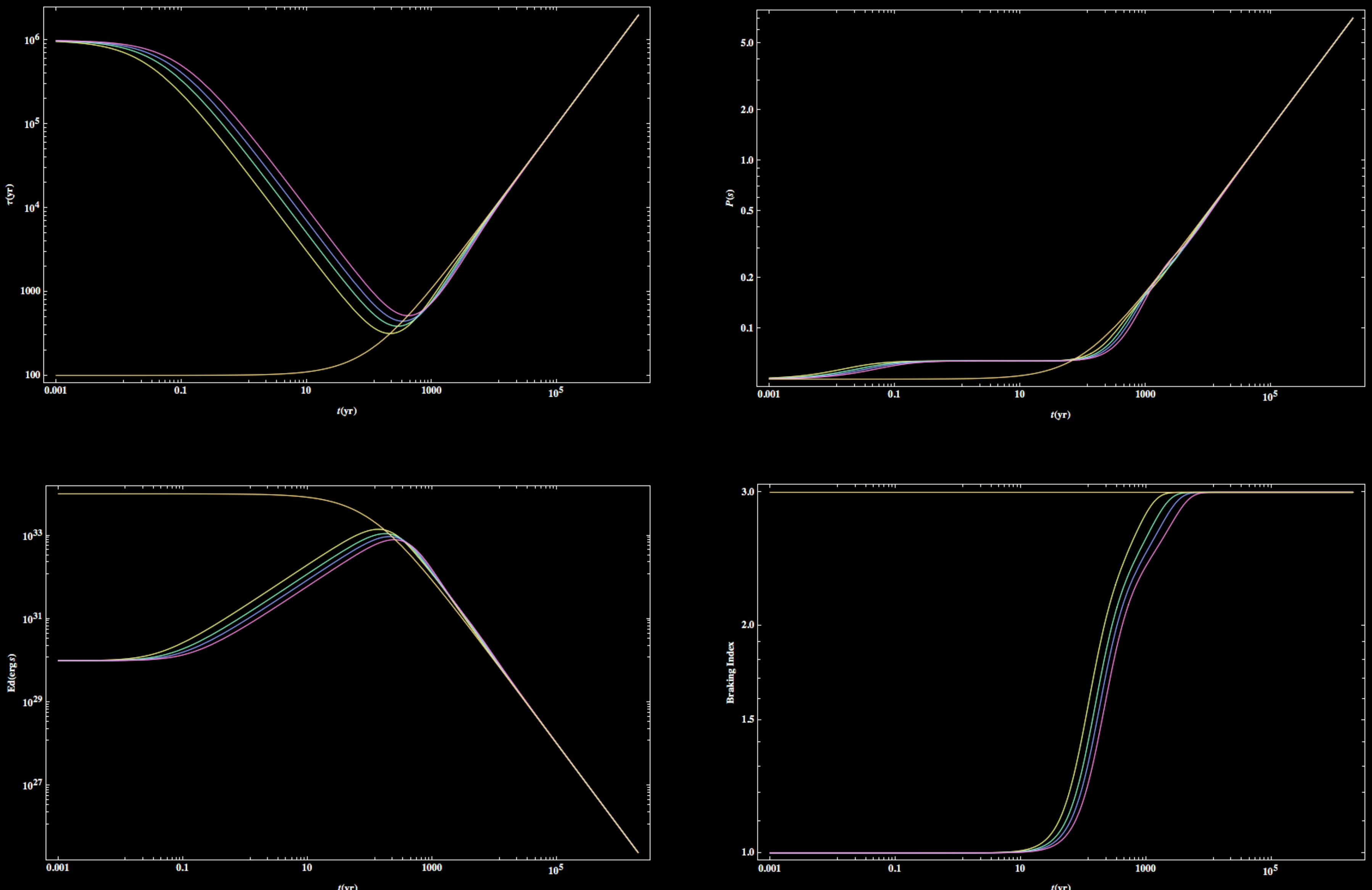
$$\Delta E = E - E_0 = \frac{(n-1)}{2}\left(\tau\dot{E} - \tau_0\dot{E}_0\right)$$

$$\tau \to \tau_0/\epsilon \qquad \dot{E} \to \epsilon\dot{E}_0$$



GROWTH OF THE MAGNETIC FIELD IN NS

LCARS VIEW



AGE-PERIOD-LUMINOSITY-BRAKING INDEX

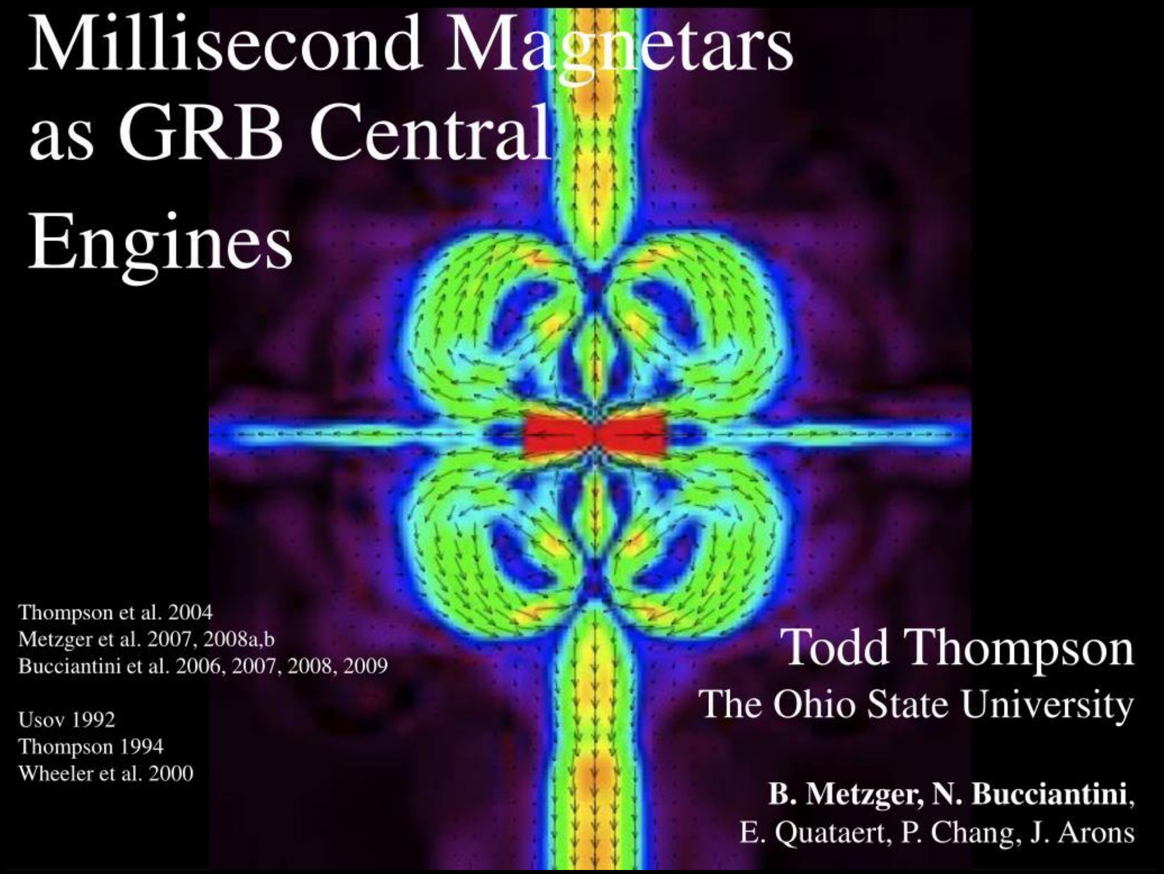
LCARS SYSTEM

23-58954

23-58954

MAGNETARS & G.U.N.S.

Millisecond magnetars, which are rapidly rotating neutron stars with intense magnetic fields, have been proposed as central engines for gamma-ray bursts (GRBs). Their rapid rotation and strong magnetic fields can drive powerful relativistic outflows, potentially explaining the energy and variability observed in GRBs.



23-58954

23-58954

ANALYSIS

PRIMARY

23-58954

SENSOR MODE

LCARS ACCESS

02-74656

MAGNETARS & G.U.N.S.

Observational manifestations of neutron stars are surprisingly varied, with most properties totally unpredicted. The challenge is to establish an overarching physical theory of neutron stars and their birth properties that can explain this great diversity.

03-74205

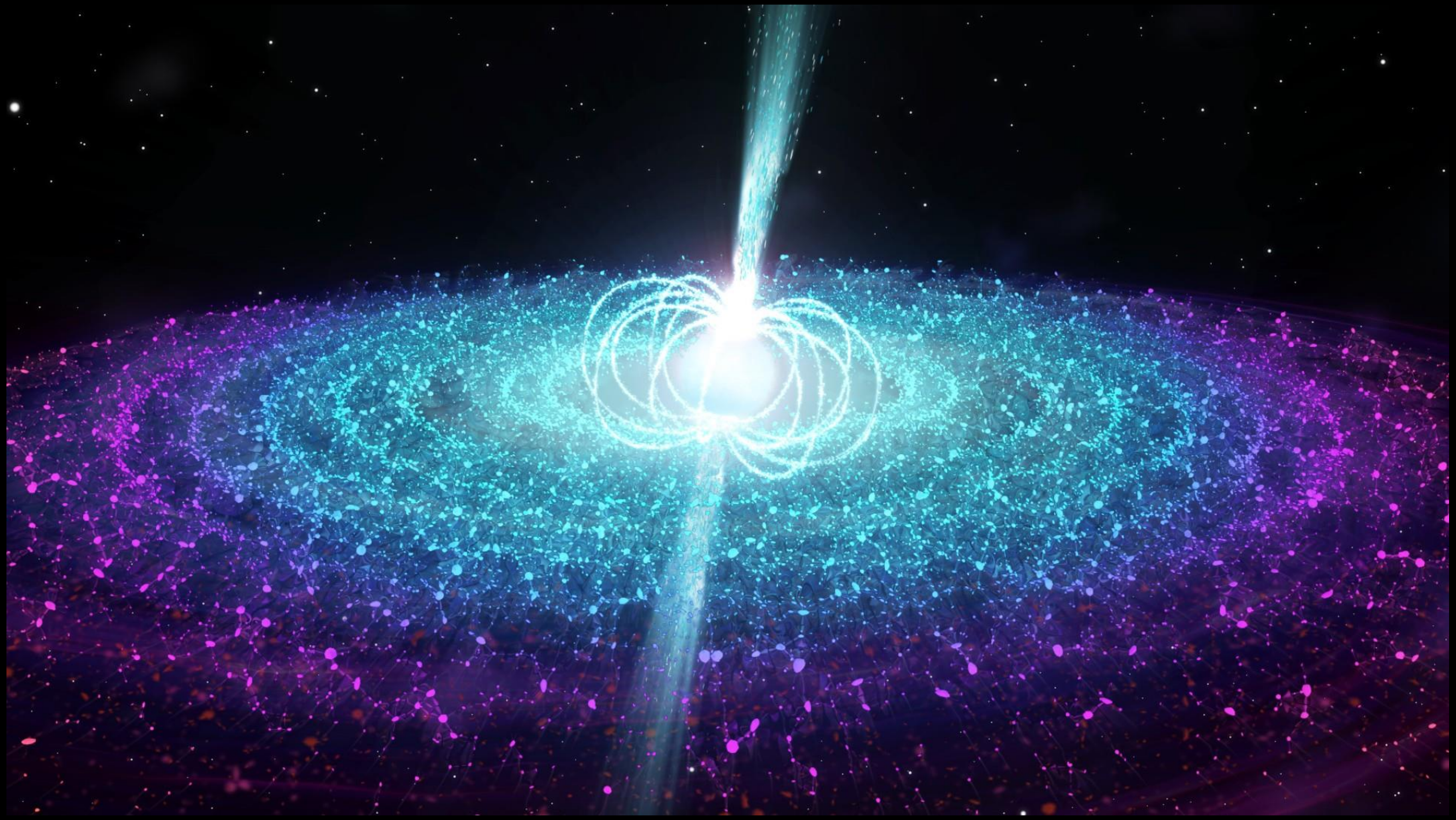
04-78105

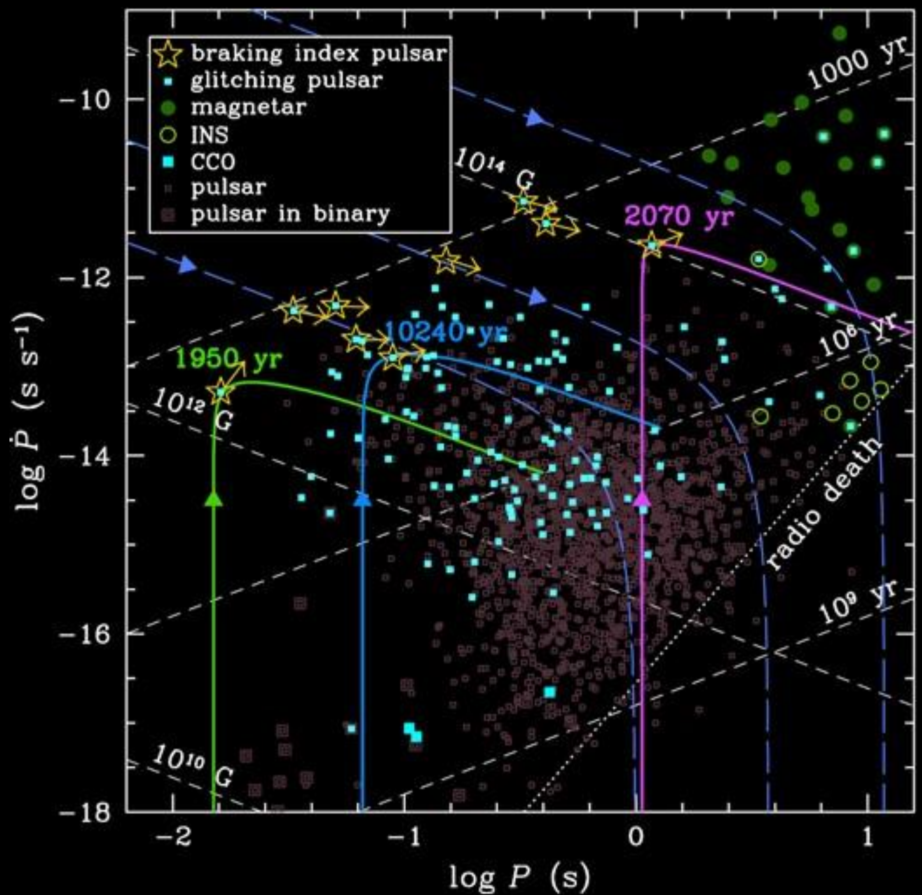
05-80102

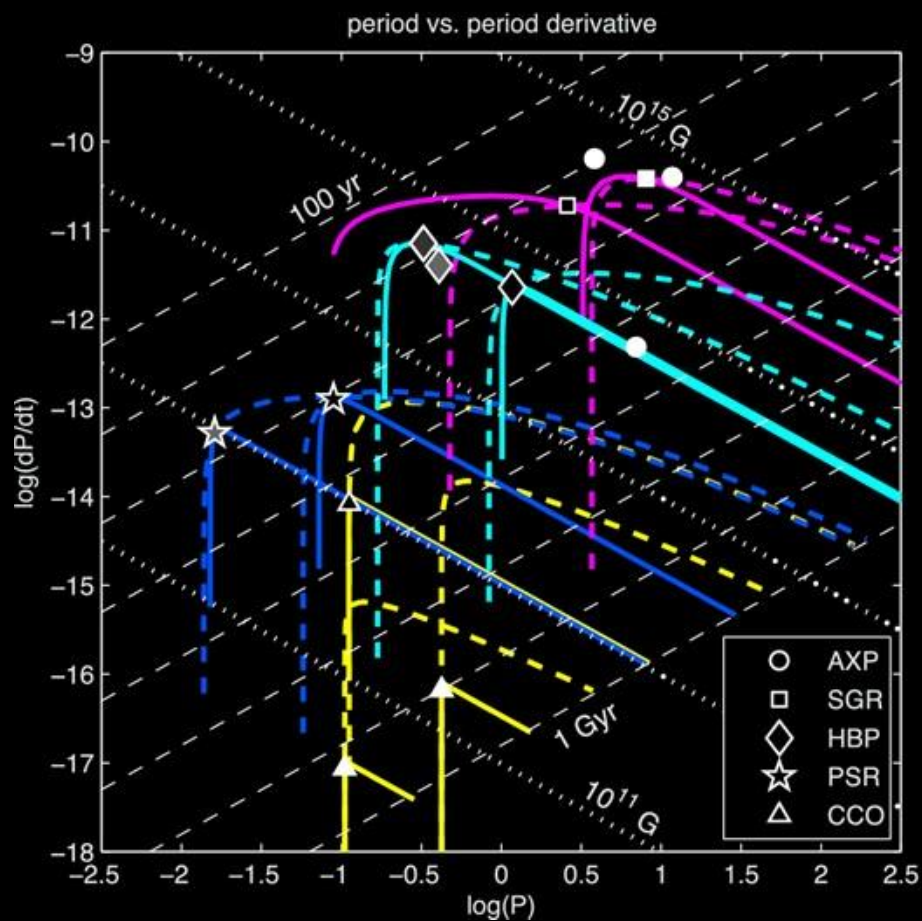
06-1701E

SCAN

NAVIGATION







PLOT OF EVOLUTIONARY TRAJECTORIES

RECOMMENDED BIBLIOGRAPHY

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- Geppert, U., Page, D., and Zannias, T. (1999). Submergence and re-diffusion of the neutron star magnetic field after the supernova. *Astronomy Astrophysics* 345, 847–854.
- Bernal, C. G., Page, D., and Lee, W. H. (2013). Hypercritical accretion onto a newborn neutron star and magnetic field submergence. *Astrophysical J.* 770, 106. doi:10.1088/0004-637x/770/2/106.

FINAL REMARKS

- During the last several years the zoo of young isolated NSs started to look not so unexplainably motley. Some evolutionary links between different types of sources are established, and more are coming with the help of the concept of emerging magnetic field.
- Following Blandford and Romani (1988), we propose a model with initial growth of magnetic field in these objects. The evolutionary implications seen, until now, not to have been followed up completely. A link between CCOS and XDINs seem feasible.

END TRANSMISSION

PLEASE REPORT MALFUNCTIONS TO ASTROUNAL STAFF ON DUTY

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