Diagnosis of PWN dynamics using their filamentary structure

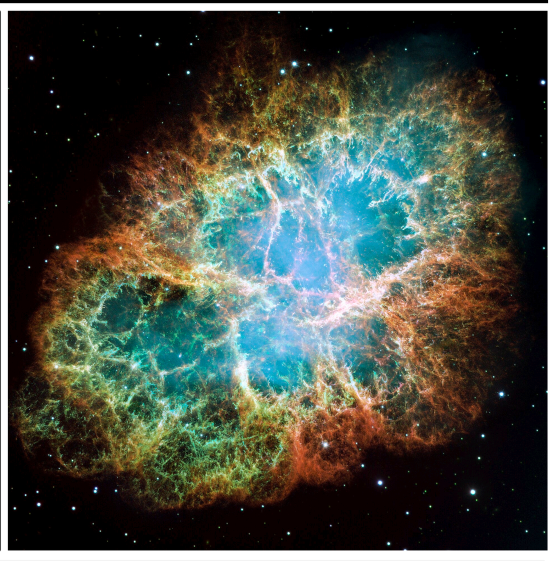
Department of Physics and Astronomy

Soham Mandal, Paul Duffell, Ziwei Ding, and Dan Milisavljevic
Department of Physics and Astronomy, Purdue University

PURDUE UNIVERSITY

ABSTRACT

The web of filaments in pulsar wind nebulae (PWNe) such as the Crab are believed to be due to turbulence from the interaction of the pulsar wind with the stellar ejecta. We show using 3D hydro models that these filaments can be formed due to hydrodynamic Rayleigh-Taylor Instability (RTI), without requiring large scale magnetic fields. We examine the evolution of the filament morphology as the pulsar wind overtakes the dense inner ejecta and blows out into the steeply thinning outer ejecta. We also study the impact of spindown of the central pulsar, and an aspherical (equatorial) wind. To test these models, we compare the three-dimensional reconstruction of the velocity field of the Crab nebula to our results. We find that the structure of the Crab requires that (a) the wind has blown out into the outer ejecta, and (b) the central pulsar has spun down considerably.



HYDRO MODELS

- The PWN model assumes a homologously expanding stellar ejecta, with a double power-law density profile.
- The inner and outer ejecta have density profiles $\rho \propto r^{-m}$ and $\rho \propto r^{-n}$ respectively, where we use m=0,2 and n=9,11.
- The central pulsar drives a wind that's spherically symmetric and of constant luminosity unless mentioned otherwise.
- An equatorial wind and a wind with declining luminosity (corresponding to pulsar spindown) are also considered.
- Calculations were performed using Sprout[1], a second order expanding mesh hydro code.

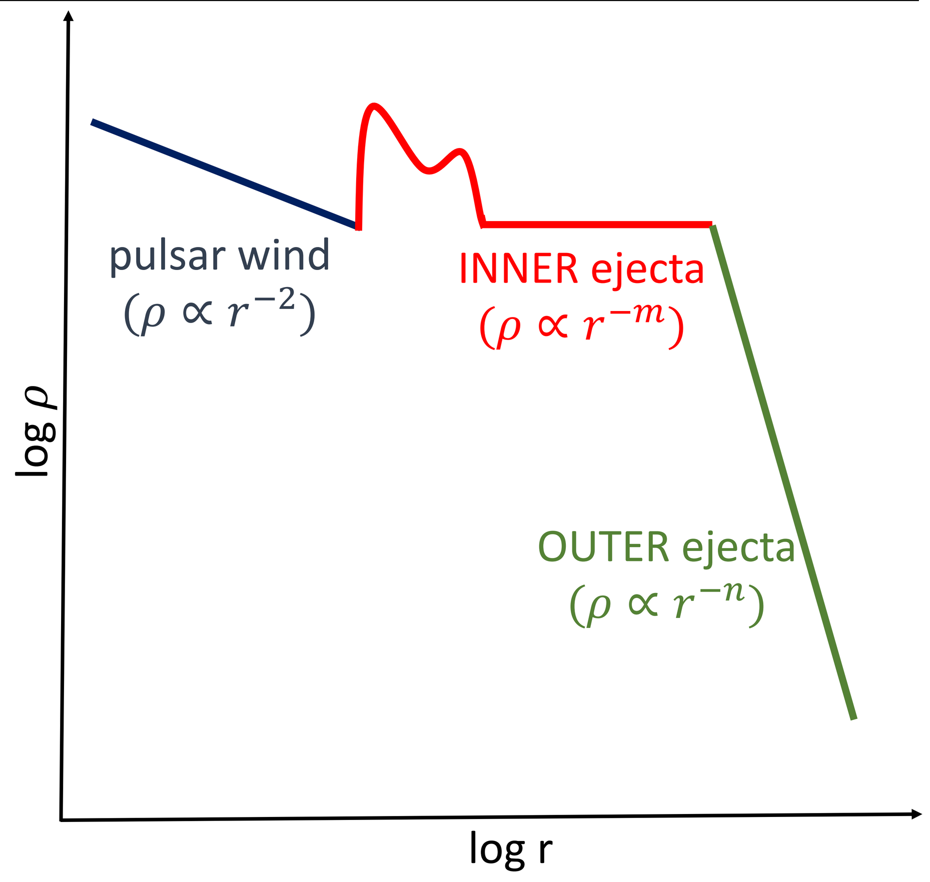


Fig 1. Density profile of the stellar ejecta for the PWN model.

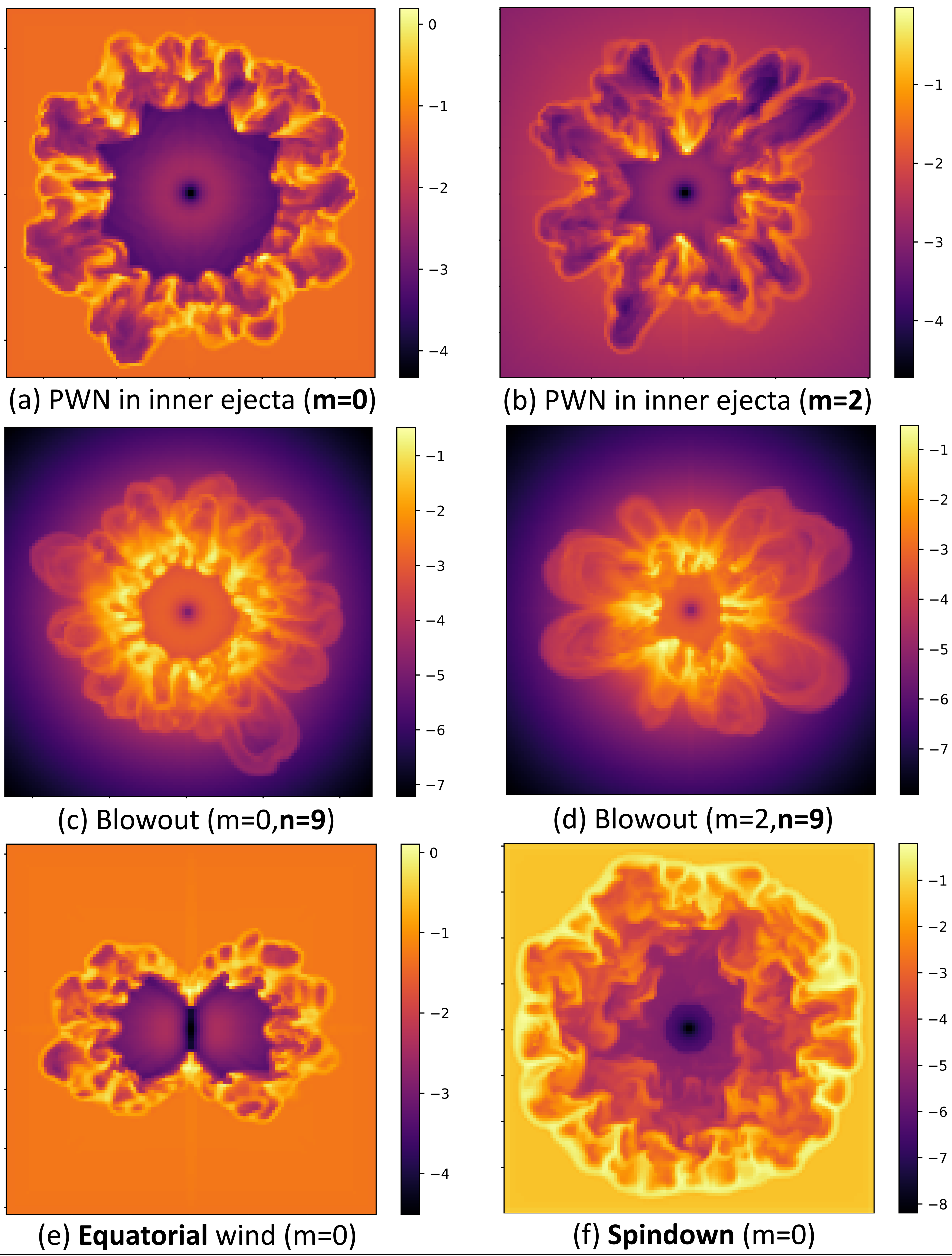


Fig 2. Mid-plane slice of logarithm of density for the PWN models.

QUALITATIVE FEATURES OF THE MODELS

- All models exhibit a rich network of blobs and filaments generated by RTI.
- The PWN expands self-similarly when confined by the inner ejecta; however even a modestly steep density (m=2) strongly corrugates the forward shock.
- The RTI blobs become considerably bigger when the shock blows out into the outer ejecta, as known before [2]. Heavier filaments are overtaken by lighter ones.
- The RTI filaments are preserved considerably longer when the pulsar spins down.
- The equatorial wind results in filamentary structures being concentrated near the equator, as expected.

RADIALLY INTEGRATED VELOCITY MAPS

- Anisotropies seen in the PWN models in Fig 2 are better quantified by projecting them onto the spherical surface of the PWN.
- This is done by integrating radial velocity in the shocked plasma along radial rays, producing a map in polar angles θ and ϕ.
- Mollweide projections of these maps are shown in Fig 3.

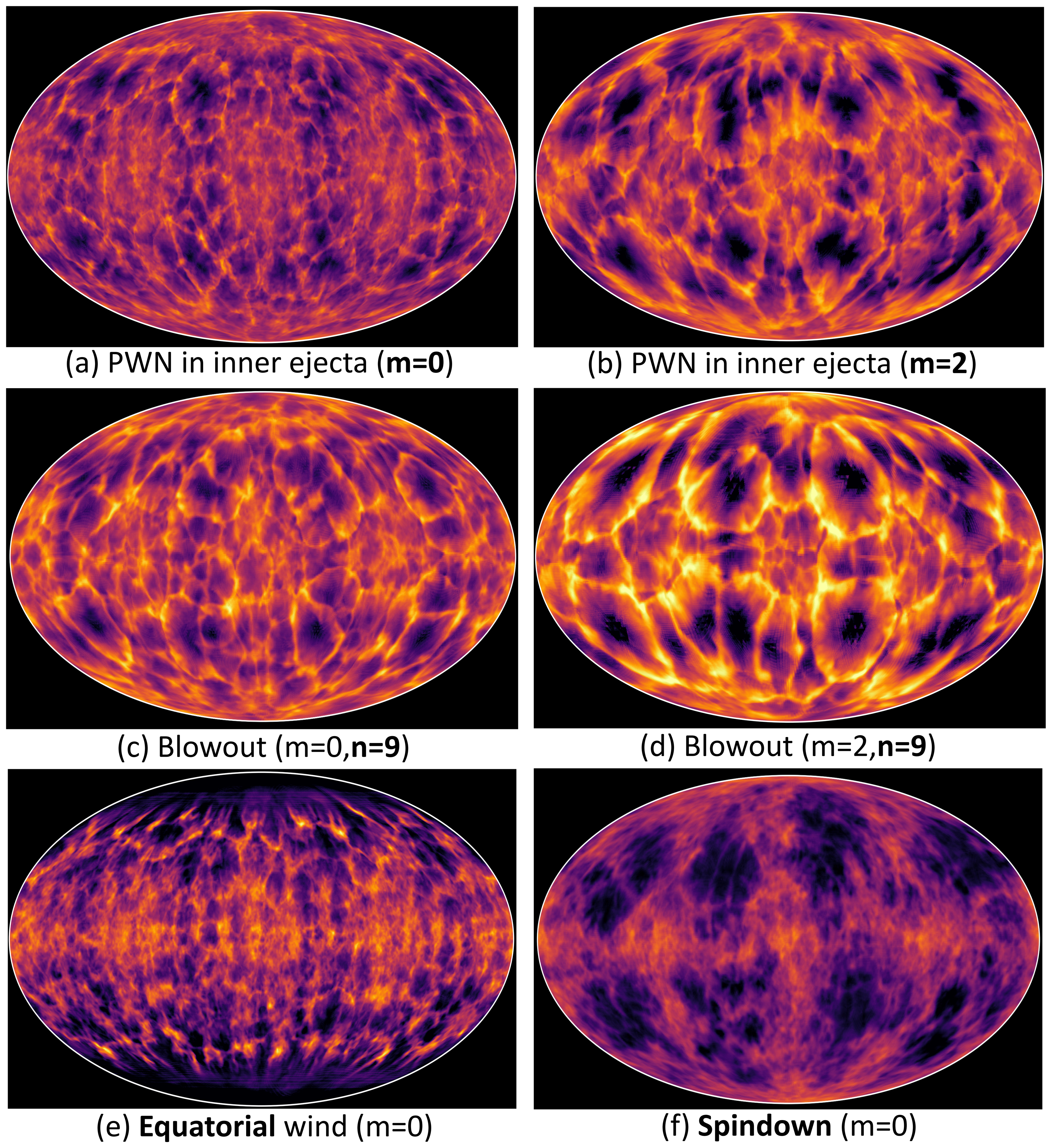
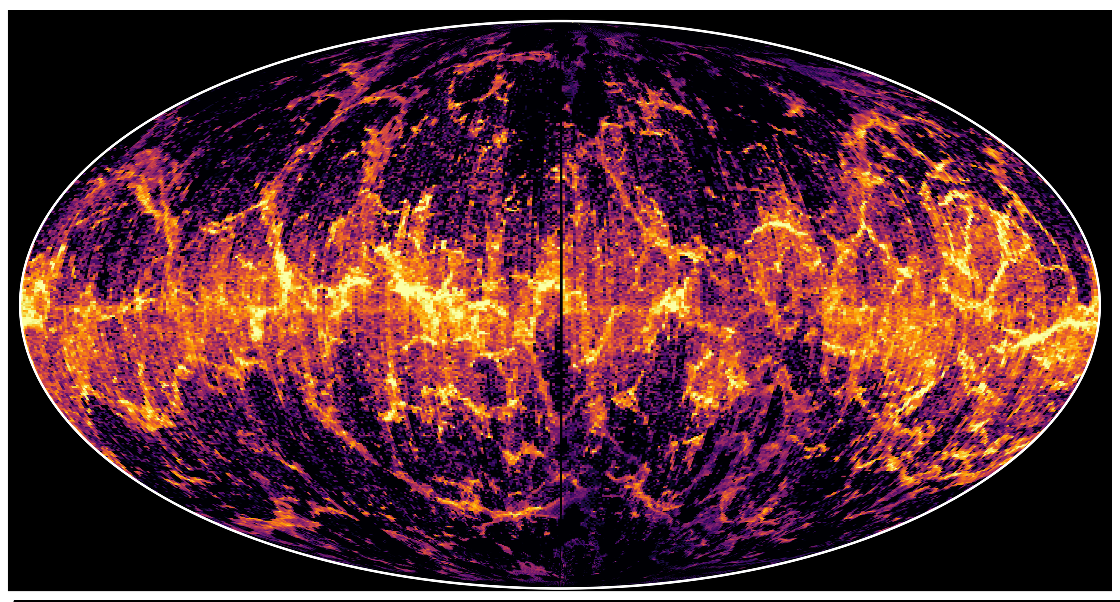


Fig 3. Mollweide projection of the radially integrated velocity map for the PWN models.

RADIALLY INTEGRATED VELOCITY MAP OF THE CRAB



- We retrieve 3D velocity information for the Crab from spectral data cubes obtained using the SITELLE instrument[3,4].
- This is used to make a radially integrated velocity map of the Crab nebula (Fig 4), similar to the ones in Fig 3.

Fig 4. Mollweide projection of the radially integrated velocity map of the Crab nebula.

INFERENCES

- The effect of pulsar spindown is to preserve large filaments for longer and create large voids in the velocity maps.
- Blowout produces strong contrasts in the velocity maps (large spread of velocities, seen in bright yellow here).
- Equatorial wind causes concentration of structures near the equator.
- You could **reproduce the Crab** with all three features!

REFERENCES

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