On the radio emission of planets around pulsars.

Preliminary thoughts.

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The first exoplanets were discovered around pulsars

Two pulsars with planets, discovered in 1992 and 1993, through pulsar timing method (Doppler shift of the pulsar's period P).

Name	P (s)	Ω_* (s^{-1})	B_* (Gauss)	M_* ($M_\odot$)	R_* (km)
	Star's rotation	$\Omega_* = \frac{2\pi}{P}$	Magnetic	Star's mass	Star's radius
PSR 1257+12	0.006	1010.	8.8×10^8	1.4	10.
PSR 1620-26	0.011	567	$3. \times 10^9$	1.35	10.

The planets around pulsars

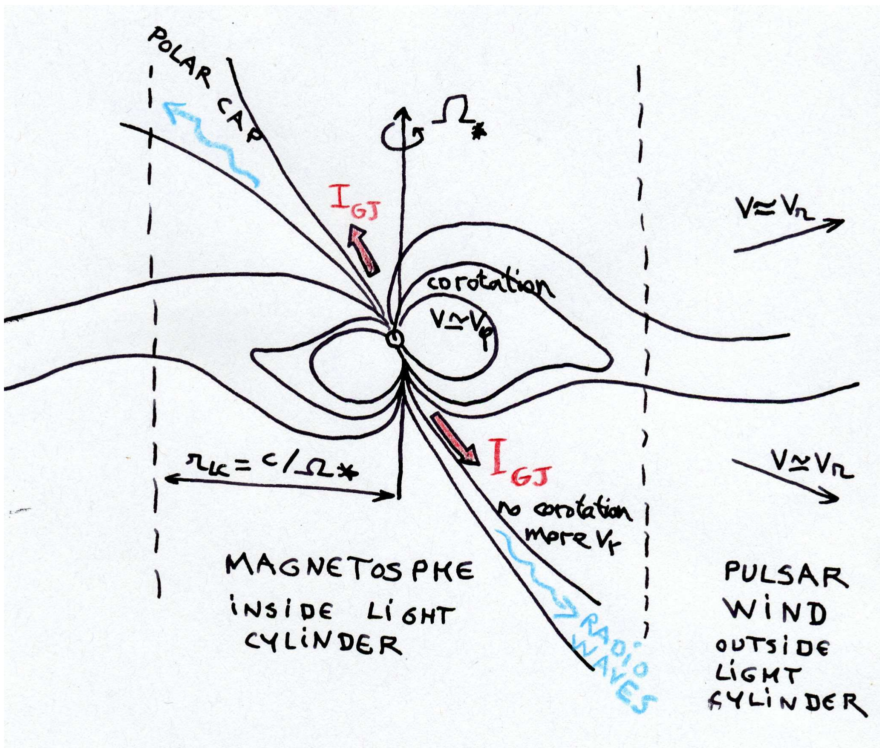
Name	M_P ($M_\oplus$)	R_P ($R_\oplus$)	P_{orb} (day)	a (AU)	e
PSR 1257+12 a	0.02	0.28	25.	0.19	0
PSR 1257+12 b	4.3	1.68	66.	0.36	0.0186
PSR 1257+12 c	3.9	1.62	98.	0.46	0.0252
PSR 1620-26 a	794	9,5	36367.	23.	

[Wolszczan 1992,Thorsett 1993]

Loss neutron star's rotational energy vs. planet orbital energy.

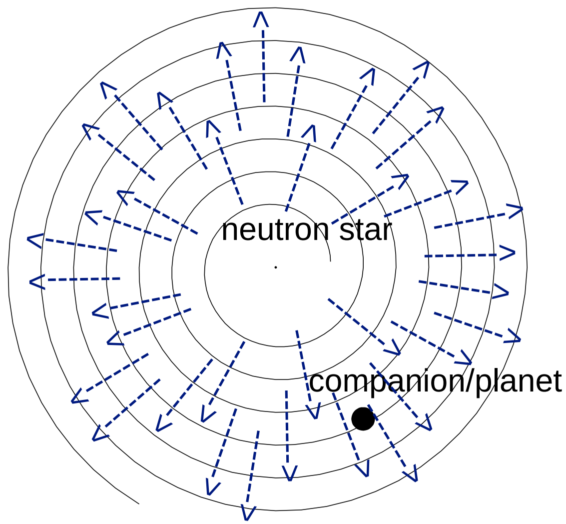
- Fast star's spin:
  A pulsar is a neutron star with a fast spin $P \sim 0.001 - 5$ s and a magnetosphere.
- Spin down
  It is observed (for every PSR) that the star's rotation slows down:
  $\dot{P} \sim 10^{-15} - 10^{-19} P$.
- Dissipation of energy of PSR B1257+12
  $\dot{E}_{rotation} = -M_I \Omega_* \dot{\Omega}_* = 4\pi^2 M_I \dot{P}/P^3 = 2. \times 10^{27}$ W.
- Orbital energy of PSR B1257+12 and its planet "a".
  $E_G = \frac{G M_* M_p}{2a} = 4. \times 10^{32}$ J.
- Comparison the dissipated energy captured through the planetary radius, and planet's orbital energy .
  $(R_p/a)^2 (E_G/\dot{E}_{rotation}) = 1,5 \times 10^6$ years for planet PSR 1257+12 "a".
- Question. With an inefficient coupling mecanism, can we expect heating, plasma acceleration and *radio emissions* ?

A pulsar's magnetosphere.



- Inner magnetosphere Complex structure. Considered as the main region of acceleration and pair production.
- Light cylinder (LC) A frontier, at radius $R = c/\omega_*$: the plasma cannot be in corotation anymore. Waves propagating along the magnetic field cannot go back from the LC to the star.
- Pulsar wind Outside the LC, an almost radial expansion of an ultrarelativistic and underdense plasma.

Pulsar-planet interaction through the pulsar wind.

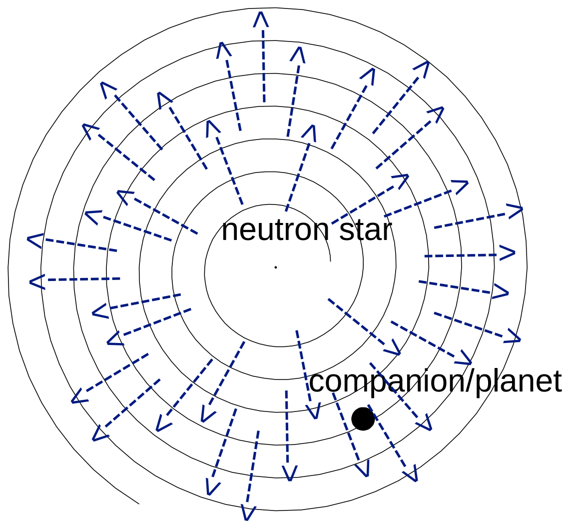


Star in the center. Black dot: planet. Black line: magnetic field line. Arrows: wind velocity $\sim c$.

Name	P (s)	r_{LC} (km)	P_{orb} (s)
Standard PSR	1.	47 000	147
Fast PSR	0.010	477	0.147

The planets ($P_{orb} >$ a few mn) are far behond the light cylinder, they orbit in the pulsar's wind.

Pulsar's winds.



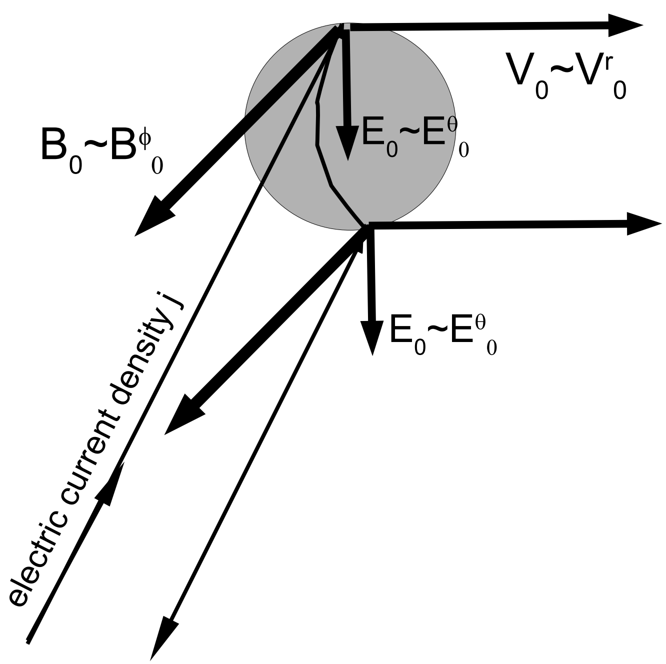
Star in the center. Black dot: planet. Black line: magnetic field line. Arrows: wind velocity $\sim c$.

- Radial flow
  $v_W \sim v_r$
- Poyting-flux dominated wind
  Highly magnetized ($B^2 >> \mu_0 \rho \gamma c^2$) and relativistic plasma (Lorentz factor $\gamma \sim 10^2 - 10^7$.)
- Quasi-azimutal magnetic field
  $B \sim B_\phi >> B_{poloidal}$
- Possibly sub-Alfvénic wind
  $v_W \sim c$, $V_A \sim c$, until 100's of r_{LC}, (models) $v_W < V_A$

[Goldreich, Lynden-Bell 1969, Michel 1969, 2005, Contopoulos, Kazanas 1999, Bucciantini et al. 2006]

Alfvén wings

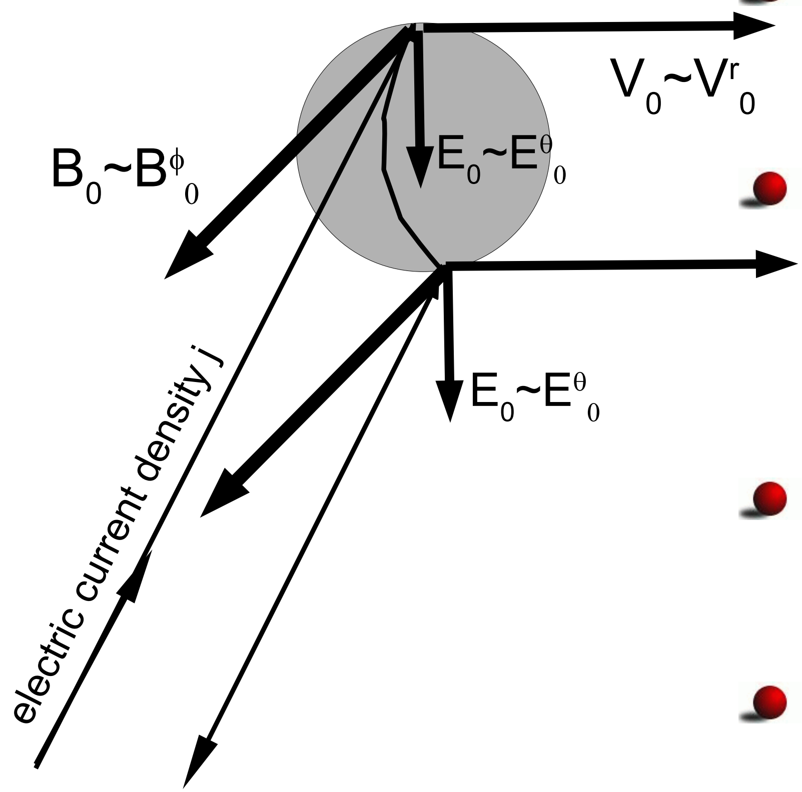
- The engine: Unipolar inductor. In the wind, $E = -v_{wind} \times B_\phi$ induces a potential drop on each side of the planet.



Unipolar inductor and Alfvén Wing (AW) current.

- Simple hypothesis.
  Incompressible uniform plasma (OK at 1st order [Wright and Schwartz 1990]). Non-relativistic [Neubauer 1980] and relativistic flow [Mottez Heyvaerts, in prep].
- Propagation of Alfvén waves almost only along the magnetic field // $V_A \sim V_{A,\phi}$ in the wind's frame of reference.
- Planet : conducting, and free electrons (ionosphere)
- Structure
  The potential drop induces a current. This current is closed along the magnetic field lines, by two stationary Alfvén waves called Alfvén wings.

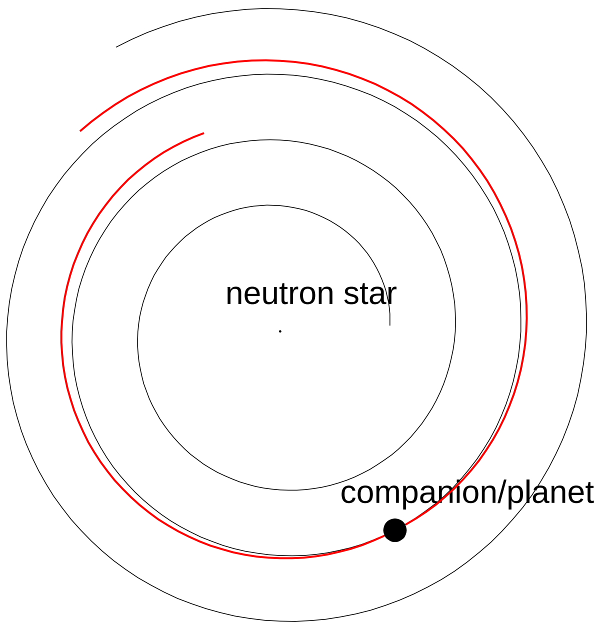
The current associated to Alfvén wings and radio emissions.



Unipolar inductor and Alfvén Wing (AW) current.

- Current closure The resistivity is those of the planet (ionosphere or ionized surface) and those of the Alfvén wave (in space).
- Alfvén wave resistivity (relativistic case)
  $$\Sigma_A = W_0 \left\{ \mu_0 c \frac{\mathcal{B}_0}{\mathcal{B}_{A0}} \left[1 + \left(\frac{V_0}{c} \frac{\mathcal{B}_{A0}}{\mathcal{B}_0} W_0 \right)^2 \right] \right\}^{-1}$$
  $\Sigma_A \sim 1/\mu_0 c$
- Estimate of the total current
  $I_{AW} = 4(E_0 - E_i) R_P \Sigma_A$ [Neubauer 1980, Mottez & Heyvaerts].
- Source of the radio emissions, comparison with the pulsar polar cap's current. Numerically, for a $P = 1$s PSR and an Earth-like planet at 0.2 UA, $I_{AW} \sim 10^{11}$ A.

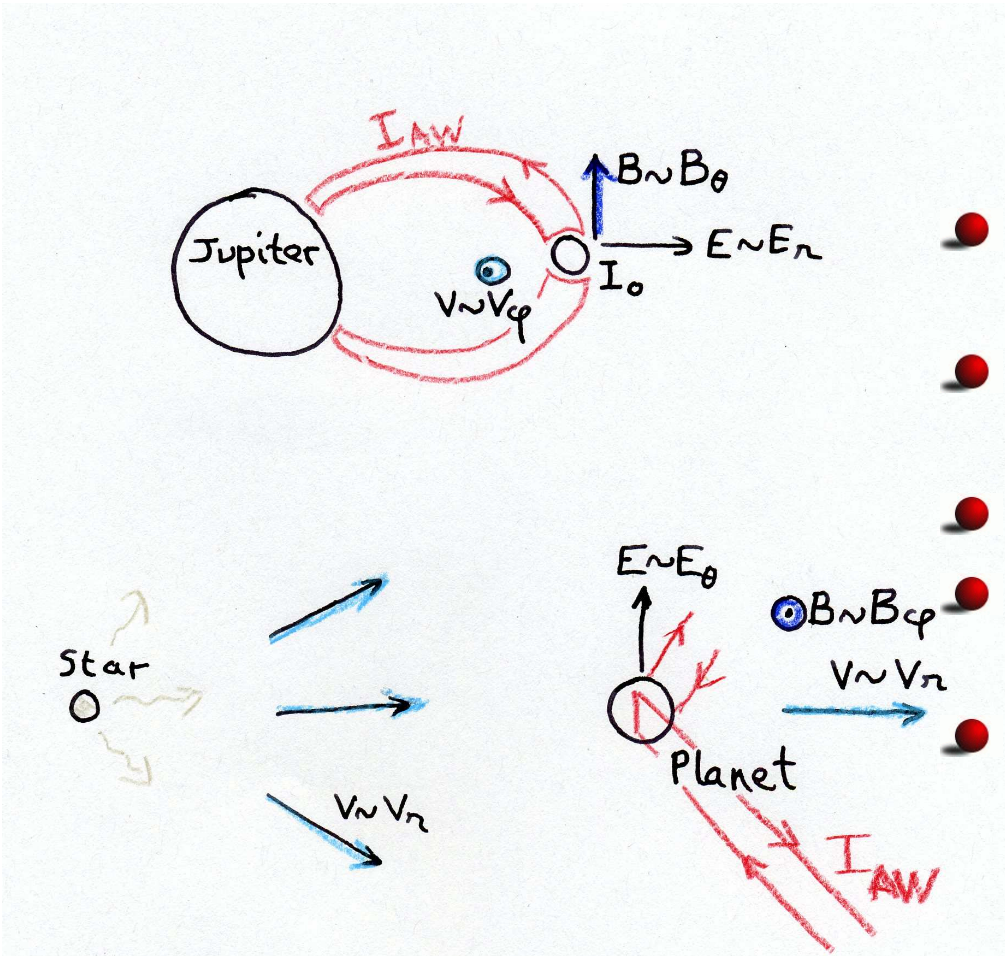
The shape of the Alfvén wings in the pulsar's wind.



Star in the center. Black dot: planet. Black line: magnetic field line. Red lines: Alfvén wings.

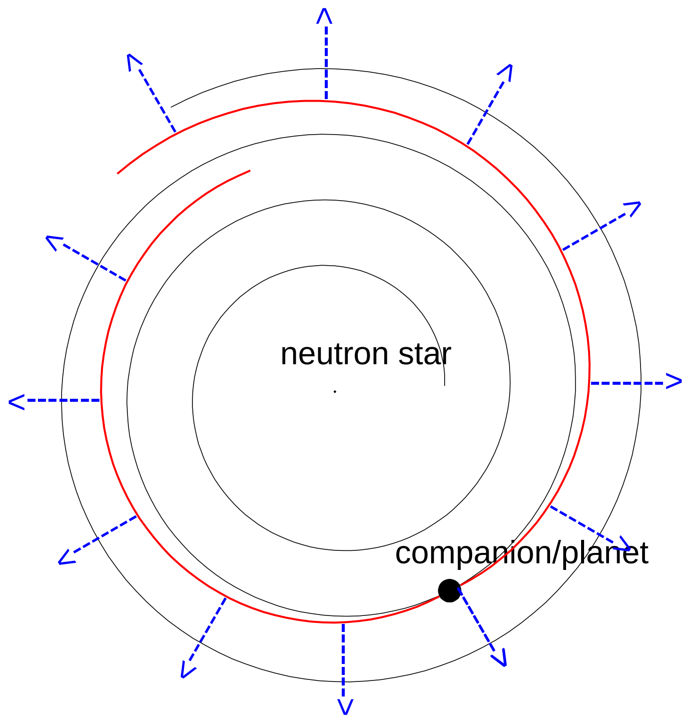
- The Alfvén wave wing/ the ribbons of current make a constant angle with the ambient magnetic field.
- The wing is connected only to the planet.

Io-Jupiter: a well explored case of Alfvén wings



- Io is immersed in a sub-Alfvenic plasma flow
- Orthogonal plasma flow and magnetic field
- An associated electric current
- Current closure along Io, the wing and *Jupiter*
- Acceleration and radio emissions

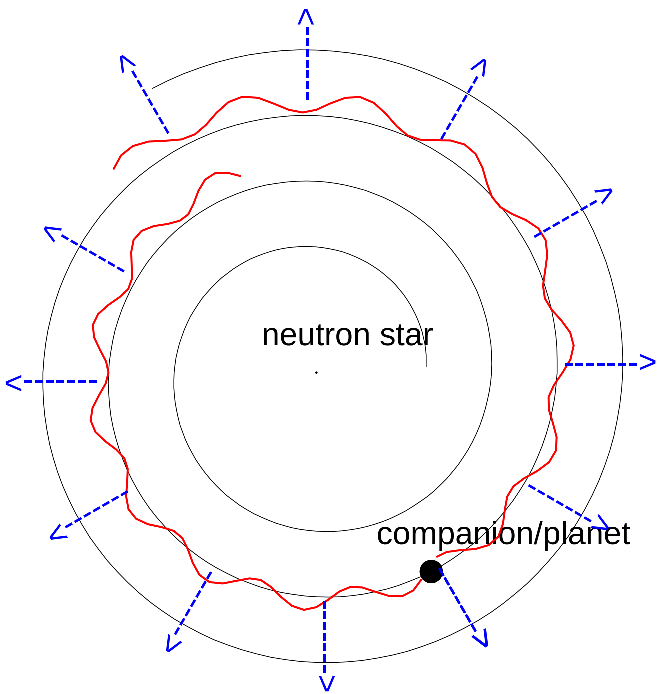
Angle of emission of the radio emissions.



Star in the center. Black dot: planet. Black line: magnetic field line. Red lines: Alfvén wings. Blue arrows: direction of radio wave emissions (radial).

- Direction of emission : relativistic aberration
  Any radiation from a flow with a Lorentz factor γ is directed along this flow, in a cone of angle $\Omega = \gamma^{-1}$ rd. Here, $\gamma \sim 10^2 - 10^7$.
- Radial radio emission from a crown
  The waves are therefore emitted radially, from all the AW.
- The direction of emission can be different from that of the pulsar.
  The PSR radiation may be emitted in the polar cap (high inclination/equator) or the slot and outer gaps (high range of inclinations). Planet : in the radial direction given by the orbital plane.

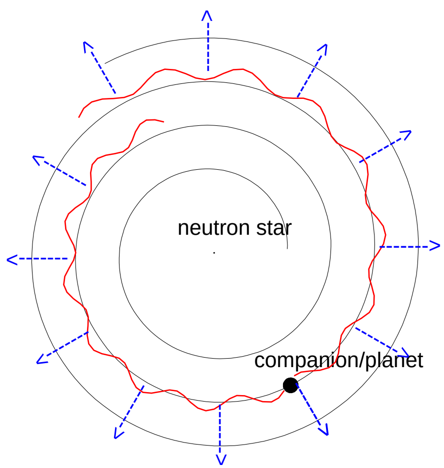
Why the Alfvén wing radio emissions would be pulsed.



Star in the center. Black dot: planet. Black line: magnetic field line. Red lines: Alfvén wings. Blue arrows: direction of radio wave emissions (radial).

- Inclination of the star's magnetic field /rotation axis.
- Modulation of the shape of the Alfvén wings.
  Modulation with a wavelength $\lambda = 2\pi V_A/\Omega_* \sim 2\pi c/\Omega_*$.
- Modulation of the angles of emission.
  And the frequency of the pulses $\Omega_{observed} = \Omega_* \pm \Omega_{orb}$.

The intensity of emitted and received Alfvén wind radio emissions.



- Source of the radio emissions, comparison with the pulsar polar cap's current.
  Numerically, for a $P = 1$s PSR and an Earth-like planet at 0.2 UA, $I_{AW} \sim 10^{11}$ A. For comparison, the pulsar's current i.e. Goldreich-Julian current is $I_{GJ} = 2. \times 10^{11}$ A.
- Comparison of the sources of free energy.
  The current carried by the Alfvén wings and the planet is of the same order as the pulsar's current around the neutron star. And... the PSR current is considered as the engine of the plasma acceleration and the radio-emissions !
- No present study of the mecanisms of coherent emission.
- Distribution of the radiated energy along a crown.
  If a beam angle $1/\gamma \sim 1^o$, radio emission from AW all along the orbit makes a solid angle $\Omega \sim 400^o$. On a PSR, sources distributed along the much narrower polar cap, $\Omega \sim 1 - 10^o$. If same overall intensity, a planet in a PSR wind would be ~ 100 less bright than the PSR. Such ratios of brightness exist among pulsars. There remains some hope of detection.

How to differentiate PSR from AW radio emissions ?

Conjectures and questions.

- No Doppler effect if circular orbit.
- Doppler effect in case of an elliptic orbit.
- Range of frequency, mecanisms of coherent emission ?
- What kind of modulation of the AW pulse characteristics over an orbital period ?

A project for LOFAR ?

- Search for cyclic variation of the pulse characteristic, over days/weeks.
- Pulse duration, how to make the distinction with other pulsar timing effects ?
- In the pulsar wind, lower magnetic field, effect on the low freq. spectrum ?

Summary

A planet orbiting around a pulsar would be immersed in an ultrarelativistic underdense plasma flow.

It would behave as a unipolar inductor, with a significant potential drop along the planet. As for Io in Jupiter's magnetosphere, there would be two stationary Alfvén waves (Alfvén wings) attached to the planet.

The AW are supported by strong electric currents, comparable to those of a pulsar. It would be a cause of strong radio emissions, with sources all along the AW, highly colimated through relativistic aberration.

There would be a chance to detect these radio-emissions from Earth.
The emission would be pulses as for ordinary pulsars, not highly dependent on the planet-star-observer angle.

Still preliminary. Further work to be done.