Apparently Ultra-long Period Radio Sources from Self-lensed Pulsar Black Hole Binaries

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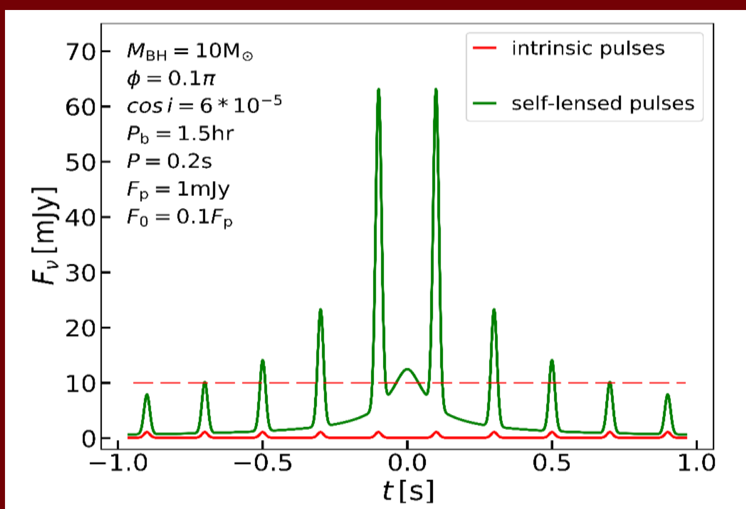
Abstract: Pulsar-black hole (BH) close binary systems, which have not been found yet, are unique laboratories for testing theories of gravity and understanding the formation channels of gravitational-wave sources. We study the self-gravitational lensing effect in a pulsar-BH system on the pulsar's emission. Because this effect occurs once per orbital period for almost edge-on binaries, we find that it could generate apparently ultra-long period (minutes to days) radio signals when the intrinsic pulsar signal is too weak to detect. Each of such lensed signals, or 'pulse', is composed of a number of amplified intrinsic pulsar pulses. We estimate that a radio telescope with a sensitivity of ~10 mJy could detect approximately 3 systems that emit such signals in our galaxy. The model is also applied to three recently found puzzling long-period radio sources: GLEAM-X J1627, PSR J0901 and GPM J1839. To explain their observed signal durations and periods, the masses of their lensing components would be $\sim 10^4$, ~ 4 and $\sim 10^{3-6}\ \mathrm{M}_\odot$, respectively, with their binary coalescence times ranging from a few tens to thousands of years. However, compared to observational constraints, our model predicts higher merger rates and larger period decay rates for these sources.



The light curve of the self-lensed pulses.

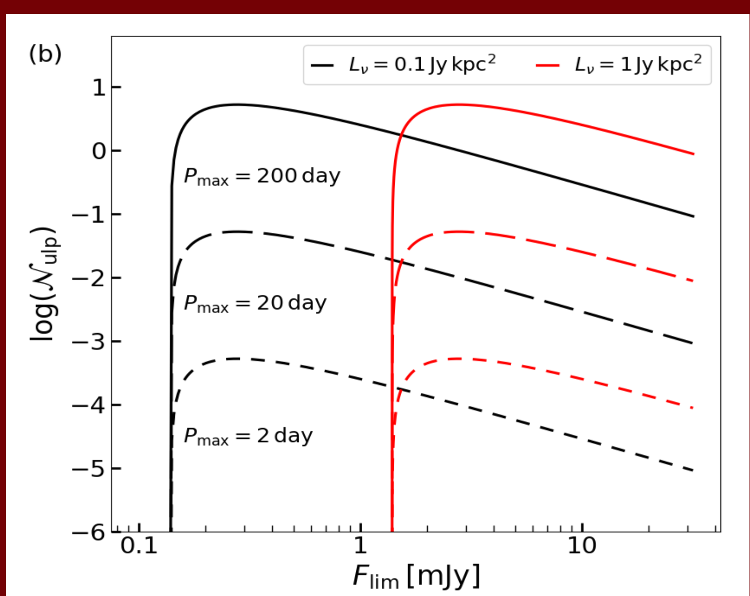
-- As pulsars are compact object, they can be treated as point-like sources. Thus the amplification of point source can be used :

$$A=\frac{u^2+2}{u\sqrt{u^2+4}}\approx\begin{cases}u^{-1}, & for\ u<1\\ 1+2u^{-4}, & for\ u\geq 2\end{cases}$$

-- Assuming gaussian shape intrinsic pulses: $F(t)=F_p e^{[-2(\pi t/\rho)^2]}+F_0, -P/2<t<P/2$

-- The flux of self-lensed pulses can be derived by: $F_{\rm lens}(t)=A(u)F(t)$

-- In the figure: The green and red lines are corresponding to the self-lensing and intrinsic situation. The red dashed lines correspond to a certain detection sensitivity $F_{lim}=10\ \mathrm{mJy}$. Only when the peak flux of lensed pulses exceeds $F_{\rm lim}$ can they be detected. As the self-lensing effect happens in every orbital period, the lensed pulses will consist of apparently ultra-long period (hours to days) radio signals when the intrinsic pulsar signal is undetectable.



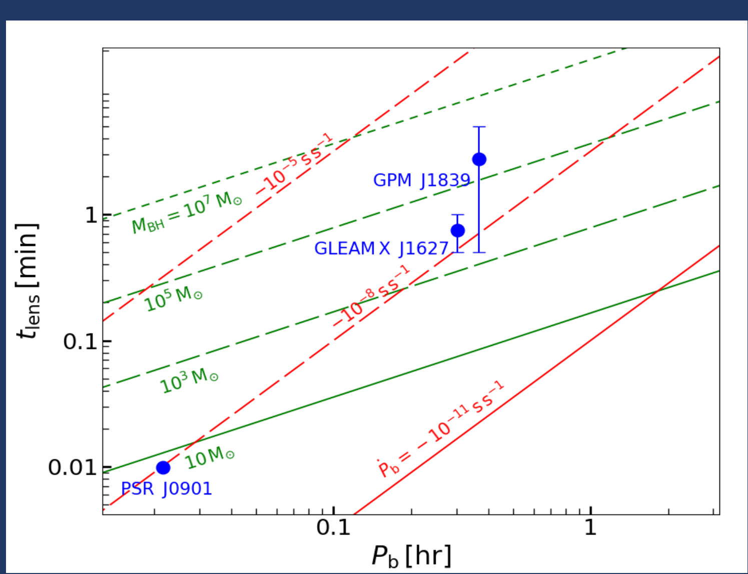
The number of observable systems in the Milky way

-- The estimated number of such ultra-long period signals from self-lensing is given as:

$$N_{\rm ulp}\approx 2.5\times\left(\frac{P_{\max}}{200\ \mathrm{day}}\right)^2\left(\frac{F_{\rm lim}}{10\ \mathrm{mJy}}\right)^{-1}\left(\frac{L_\nu}{1\ \mathrm{Jy\ kpc^2}}\right)$$

$F_{\rm lim}$ represent the sensitivity of a certain. When it at a moderate level (e.g. > 0.1 mJy for black lines), the observable number would increase as it decrease. While when it reaches a level at which the telescope can detect the intrinsic pulsar emission from every pulsar-BH binary in the Milky Way, the ultra-long period characteristics would disappear from every system.

-- Approximately 2 pulsar-BH binaries in the Milky Way with observable ultra-long period signals that can be detected by a telescope with a sensitivity of $10\ \mathrm{mJy}$.



The parameter space

-- Taking the duration of the ultra-long period signal as the self-lensing duration $t_{\rm lens}$ and the signal period as orbital period $P_{\rm b}$. The green and red lines are the contours for BH mass and orbital period decay rate, respectively.

-- The recently found puzzling radio sources: the 18.2 min GLEAMX, the 76s J0901 and the 22 min GPM are also plotted. The implied BH masses of them are $\sim 10^4$, ~ 4 and $\sim 10^{3-6}\ \mathrm{M}_\odot$, respectively, with the decay rates of orbital period $>10^{-8}\mathrm{s\ s^{-1}}$, which is inconsistent with their signal $\dot{P}$ that constrained from observation.

-- A merger rate could also derived from their period decay rate, which is much larger than that constrained from currently GW observations.

Conclusion:

-- The self-lensing effect in Pulsar-BH binaries would brighten the intrinsic emission from pulsar, which make it possible to observe those dim pulsars and generate unique ultra-long period radio signals, showing up as a slow pulsar.

-- Approximately 2 pulsar-BH binaries in the Milky Way with observable ultra-long period signals that can be detected by a telescope with a sensitivity of $10\ \mathrm{mJy}$.

-- The recently found puzzling radio sources are unlikely the self-lensed pulsars, both because the predicted decay rates of the signal period exceed the observational constraints, and that the implied merger rates for these sources are much higher compared to the rates inferred from GW observations.

Abstract: Pulsar-black hole (BH) binary systems, which have not been found yet, are unique celestial laboratories for testing relativistic theories of gravity and understanding the formation of gravitational wave sources. We study the self-gravitational lensing effect in a pulsar-BH system on the pulsar's emission. Because this effect magnifies the pulsar signal once per orbital period, we find that it may generate apparently ultra-long period (days) radio signals when the intrinsic pulsar signal is undetectable. We estimate that there may be hundreds of such systems in our galaxy that are observable for a radio telescope with a sensitivity of $\sim 10\, mJy$. The model is applied to two recently found puzzling long-period radio sources: J162759.5-523504.3 and PSR J0901-4046. If these two sources are self-lensed pulsar-BH systems, the BH mass will be $\sim 10^4$ and $\sim 10^2$ solar masses, respectively. Their coalescence time will become so small (~year) that they should have merged by now.

Pulsar-black hole (BH) close binary systems, which have not been found yet, are unique laboratories for testing theories of gravity and understanding the formation channels of gravitational-wave sources. We study the self-gravitational lensing effect in a pulsar-BH system on the pulsar's emission. Because this effect occurs once per orbital period for almost edge-on binaries, we find that it could generate apparently ultra-long period (minutes to days) radio signals when the intrinsic pulsar signal is too weak to detect. Each of such lensed signals, or 'pulse', is composed of a number of amplified intrinsic pulsar pulses. We estimate that a radio telescope with a sensitivity of $\sim 10\, mJy$ could detect approximately 3 systems that emit such signals in our galaxy. The model is also applied to three recently found puzzling long-period radio sources: GLEAM-X J1627, PSR J0901 and GPM J1839. To explain their observed signal durations and periods, the masses of their lensing components would be $\sim 10^4$, ~ 4 and $\sim 10^{3-6}$ solar masses, respectively, with their binary coalescence times ranging from a few tens to thousands of years. However, compared to observational constraints, our model predicts higher merger rates and larger period decay rates for these sources.