Recovering the pulse profiles and polarization position angles of some pulsars from interstellar scattering *

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Abstract Interstellar scattering causes broadening and distortion in the mean pulse profiles and polarization position angle (PPA) curves of pulsars, especially pulse profiles observed at lower frequencies. This paper implements a method to recover the pulse profiles and PPA curves of five pulsars which have obvious scattered pulse profiles at lower frequency. It reports a simulation to show the scattering and descattering of pulse profiles and PPA curves, and as a practical application the lower frequency profiles and PPA curves of PSR 1356–60, PSR 1831–03, PSR 1838+04, PSR 1859+03 and PSR 1946+35 are obtained. It is found that the original pulse profiles and PPA curves can be recovered.

Key words: stars: pulsar— interstellar medium

1 INTRODUCTION

Interstellar medium (ISM) scattering broadens the intrinsic lower frequency pulse profiles of pulsars and causes flattening and distortion of the polarization position angle (PPA) curves (Li & Han 2003; Karastergiou 2009) to some extent, according to the observed frequency and distribution scale of the ISM which is located between the pulsar and the observer. The scattering of pulse profiles has been studied extensively since the first observation of the scintillation of pulsars (Scheuer 1968). Since then, pulsar researchers have developed several ISM scattering models which are the thin screen model (Rankin et al. 1970; Komesaroff et al. 1972), the thick screen model and the extended screen model (Williamson 1972), based on the observable effects of the temporal broadening of pulse profiles and the assumable scale of a scattering screen in the ISM. The scattering effect of the pulse broadening and the flattening of PPA curves have been studied frequently by many authors (e.g. Komesaroff et al. 1972; Rickett 1977; Li & Han 2003) and the distortion of PPA curves with orthogonal jumps by Karastergiou (2009). They used the higher frequency mean pulse profile without

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obvious scattering as the intrinsic pulse profile and convolved it with scattering models to obtain similar pulse-shapes and PPA curves to the observed scattered lower frequency pulse profiles. Only a few of them have performed deconvolution to recover total intensity pulse profiles of lower frequency from scattering (Weisberg et al. 1990; Kuz'min & Izvekova 1993; Bhat et al. 2003). This paper revisits the method of Kuz'min & Izvekova (1993) to restore the total intensity pulse profiles of pulsars and extends it to the restoration of linear intensity profiles and PPA curves for another five pulsars. The scattering broadening time scales of these pulsars have been obtained from the best fit for three different scattering models. The scattering time scale is a key parameter in all scattering models, and depends on observing frequency and dispersion measure (DM) (Ramachandran et al. 1997).

Descattering compensation for the first Stokes parameter I(t) of the scattered pulse signal was performed by Kuz'min & Izvekova (1993), and their method worked well for recovering the original low-frequency pulse profiles of the Crab pulsar. However, when discussing the restoration of the other Stokes parameters, we consider whether all the Stokes parameters are scattered the same way as I(t). In the early works of Komesaroff et al. (1972) and Rickett (1977), they assumed that the scattering effect may be approximated by convolving each of the time-dependent Stokes parameters of an unscattered pulse with a scattering model under certain assumptions. In the research note of Li & Han (2003), based on the works of Macquart & Melrose (2000), they simply assumed that the scattering process works similarly on all Stokes parameters. By using that assumption in their convolution method, they explained the scattering effect on pulse broadening and on PPA curve flattening well, but their approach does not work properly when applied to the deconvolution method of Kuz'min & Izvekova (1993) to recover the shape of the PPA curve. This research paper uses the same method as Kuz'min & Izvekova (1993) to recover the total intensity profile I(t). To recover the linear intensity and the PPA curve, this paper assumes that the complex number form of Stokes parameters, Q and U, may scatter the same way as I(t). The Stokes parameters Q and U have been treated as the real and the imaginary components of a complex number, respectively (Tinbergen 1996), and such a treatment is also applied in PSRCHIVE¹ in the section "Complex-Valued Rotating Vector Model." These assumptions and methods are applied to recover the pulse intensity profiles and PPA curves of some pulsars in Section 3, the results are discussed in Section 4, and the conclusions are presented in Section 5.

2 SCATTERING MODELS AND METHOD

This paper tests all three different kinds of scattering models to check the scattering phenomena in pulse profiles and PPA curves. The thin screen model (Eq. (1)) assumes the signal to be scattered is approximately mid-way between the source and observer, and is altered by irregularities in the ISM; the thick screen model (Eq. (2)) is defined such that ISM irregularities are distributed over a larger scale than in the thin screen model and can be near the observer or the source; the third one is the extended screen model (Eq. (3)), in which the signal is scattered in the whole path of its propagation, so that the irregularities are spread over the whole space between the source and the observer (Williamson 1972). The functions describing these models are the following:

$$g_{\text{thin}} = \exp(-t/\tau_{\text{s}}) \qquad (t \ge 0), \tag{1}$$

$$g_{\text{thick}} = \left(\frac{\pi\tau_{\text{s}}}{4t^3}\right)^{1/2} \exp\left(\frac{-\pi^2\tau_{\text{s}}}{16t}\right) \qquad (t>0), \tag{2}$$

$$g_{\text{extend}} = \left(\frac{\pi^5 \tau_{\text{s}}^3}{8t^5}\right)^{1/2} \exp\left(\frac{-\pi^2 \tau_{\text{s}}}{4t}\right) \qquad (t > 0), \tag{3}$$

¹ http://psrchive.sourceforge.net/manuals/psrmodel/.

where τ_s is the scattering broadening time scale which can be determined through an empirical relation between wavelength (λ) and DM (Ramachandran et al. 1997)

$$\tau_{\rm s} = 4.5 \times 10^{-5} \rm{DM}^{1.6} \times (1 + 3.1 \times 10^{-5} \times \rm{DM}^3) \times \lambda^{4.4}.$$
(4)

This relation is used as a reference to set an upper limit in the process of best fit, except for PSR B1946+35.

This paper integrates the method of compensation of Kuz'min & Izvekova (1993) into the three different scattering models. Their method works efficiently to recover the original shape of pulse profiles x(t) from observed pulse profiles y(t). Here, the same method has been used to recover the total intensity pulse profiles. The recovery of the linear intensity and PPA curve will be introduced at the end of this section. When g(t) is assumed to be a scattering model or response function, the observed y(t) is the product of x(t) and g(t), and the spectrum of the recovered pulse (original pulse) can be written as (Kuz'min & Izvekova 1993)

$$X(f) = Y(f)/G(f),$$
(5)

$$Y(f) = \int y(t) \exp(-j2\pi f t) dt, \qquad (6)$$

$$G(f) = \int g(t) \exp(-j2\pi f t) dt, \qquad (7)$$

where Y(f) is the spectrum of the observed pulse, G(f) is the frequency response of the scattering screen, and the descattered restored pulse x(t) is obtained by inverse Fourier transformation

$$x(t) = \int X(f) \exp(j2\pi ft) df.$$
(8)

By using the above equations, the total intensity pulse profiles can be recovered from the scattered pulse profiles y(t). It is also possible to study the effect of scattering on pulse profiles and PPA curves by changing the descattering procedure above by using Equations (10) and (11). We tried to implement the work of Li & Han (2003) by using Equations (10) and (11) with complex treatment of Stokes parameters Q and U, and obtained the same results in explaining pulse profile broadening and PPA curve flattening caused by ISM scattering. The following are modified functions of Kuz'min & Izvekova (1993) that apply a convolution, repeating the work of Li & Han (2003). The spectrum of the scattered pulse is calculated by

$$Y(f) = X(f) * G(f)$$
⁽⁹⁾

and the scattered pulse y(t) would be written

$$y(t) = \int Y(f) \exp(j2\pi ft) df.$$
 (10)

The above equations (Eqs. (6)–(9)) were used to recover the total intensity profiles of the Crab pulsar from ISM scattering (Kuz'min & Izvekova 1993). This time they are used to recover the total intensity, linear intensity profiles and PPA curves of a few other pulsars. In the process of restoration of the Stokes parameters Q and U, it is assumed that the observed scattered Stokes parameters Q and U form a complex number z(t) = Q(t) + iU(t); p(t) is the descattered complex number from z(t). The observed spectrum of z(t) would be

$$Z(f) = \int z(t) \exp(-j2\pi ft) dt.$$
(11)

The spectrum of a descattered p(t) is

$$P(f) = Z(f)/G(f),$$
(12)

so the descattered recovered linear intensity and PPA can be obtained from

$$p(t) = \int P(f) \exp(j2\pi ft) df.$$
(13)

The complex treatment of the Stokes parameters Q and U is more practical than treating them separately as scalars. When the Q and U are tested separately as scalars using the method of recovering I(t), the results in all three models for the descattering of the PPA curves are not as expected, and fail to produce smooth swing curves (Radhakrishnan & Cooke 1969), PPA jumps, smooth flat curves or show similarity with the higher frequency pulse's PPA curves; but when Q and U are expressed as a vector over the complex plane and using the method of Kuz'min & Izvekova (1993), they produce better results, and the linear intensity and PPA curve are recovered in a more desirable way.

3 SIMULATION AND PRACTICAL APPLICATIONS

3.1 Simulation of the Scattering and Descattering of Pulse Profiles and PPA Curves

This paper describes research about a simple simulation of intensity profiles and PPA curves with three different models for scattering and descattering. As an example, the thick screen model is used. The simulated pulse profiles have a Gaussian shape, with PPA(ψ) curves following the rotatingvector model (RVM) (Radhakrishnan & Cooke 1969). We have assumed a coherent radiation that is 100% polarized, in which the degree of linear polarization in total intensity is 0.8. The Stokes parameters Q, U and V can be respectively expressed in terms of the degree of linear polarization and PPA by $Q = 0.8I \cos(\psi)$, $U = 0.8I \sin(\psi)$ and $V = 0.75 \sqrt{Q^2 + U^2}$ (van de Hulst 1957); in the simulation only Q and U are being considered. The simulated plots from (a) to (k) are shown in Figure 1; the left panel plots of (a), (b), (g), and (h) are the original pulse profiles and PPA curves; the middle panel figures of (c), (d), (i), and (j) are the scattered pulse profiles and PPA curves; the right panel figures of (e), (f), (k), and (l) are the descattered restored pulse profiles and PPA curves; the solid lines and dotted lines in normalized intensity profiles of (a), (c), (e), (g), (i), and (k) are the total and linear intensity profiles, respectively; and the dotted lines in the plots (b), (d), (f), (h), (j), and (1) are PPA curves. It can be seen from the figure of the simulation that the amount of scattering caused pulse broadening and PPA curve flattening, and if the scattering screen q(t) is definite it is in principle possible to recover the actual features of the emitting signal.

3.2 Recovering the Intensity Pulse Profiles and PPA Curves

To compensate the scattered pulse profiles and PPA curves, we searched the European Pulsar Network (EPN) online database² (Lorimer et al. 1998) for sample pulsars (Gould & Lyne 1998) which have obvious pulse profile broadening. The data from five pulsars were downloaded, four of which were previously used by Li & Han (2003) for studying the effect of scattering on pulse profiles and on PPA curves. This study's calculation used the lower frequency pulse profiles with obvious scattering to compensate for the scattering. In Figures 2 to 6, the higher frequency profiles without obvious scattering (intrinsic pulse profiles) and their PPA curves (intrinsic PPA curves) are given for comparison. The scattering time scale and some relative data from the five pulsars are given in Table 1. The three different time scales for three different scattering models are obtained by the best fit for the pulse peak (Cols. (7)–(9)), and the time scales in Col. (6) are calculated by Equation (4) (see Table 1). When calculating the best fit, in almost all pulsars the precision of those scattering time scales is approximately controlled to within 1 ms.



Fig. 1 Pulsar signal simulation for scattering and descattering. The left panel plots of (a), (b), (g) and (h) are original pulse profiles and PPA curves, the middle panel plots of (c), (d), (i) and (j) are scattered pulse profiles and PPA curves, and the right panel plots of (e), (f), (k) and (l) are descattered pulse profiles and PPA curves. In all the intensity pulse profiles, the solid lines are the total intensity and the dotted lines are linear intensity. The dotted lines in the plots of (b), (d), (f), (h), (j) and (l) are PPA curves.

Table 1 The parameters of five pulsars and their scattering time scales for different scattering models. The parameters are tabulated from Cols. (1)–(9) as pulsar name, period, dispersion measure, observed higher frequency and lower frequency, empirical value of scattering time scale by Eq. (4), time scale for thin-screen, time scale for thick-screen, and time scale for extended screen.

PSR Name	P (ms)	${ m DM} \ ({ m pc}{ m cm}^{-3})$	Freq _h (GHz)	Freq _l (GHz)	$ au_{ m em}$ (ms)	$ au_{ m thin}$ (ms)	$ au_{ ext{thick}} \ ext{(ms)}$	$rac{ au_{ ext{extend}}}{(ext{ms})}$
B1356-60	127.503335	294.133	1.560	0.660	9.88	1.0	0.5	0.6
B1831-03	686.676816	235.800	0.610	0.408	29.63	15.0	10.0	6.5
B1838-04	186.145156	324.000	0.925	0.606	22.38	15.0	3.0	1.0
B1859+03	655.445115	402.900	0.925	0.606	60.97	13.0	7.4	5.5
B1946+35	717.306765	129.050	0.610	0.408	1.87	10.0	6.0	4.0

Actually, because of the uncertainty of the scattering screen, none of the scattering models are strictly appropriate to explain the scattering effect on pulse signals independently, even if we take the pulse width evolution with observing frequency into account (Lorimer & Kramer 2005). In general, this study has tested all three different scattering models to recover the pulse profiles and PPA curves. As an example, Figures 2–6 presented the application of one of the three models for restoring the

² http://www.mpifr-bonn.mpg.de/old_mpifr/div/pulsar/data/browser.html



Fig. 2 PSR B1356–60. The dotted lines in (a) and (b) are scattered intensity profiles; in plots (c) and (d) the solid lines are descattered intensity profiles and the dotted lines are intrinsic intensity profiles for comparison; and the plots of (e), (f) and (g) are scattered, intrinsic and descattered PPA curves, respectively.



Fig. 3 PSR B1831-03. The dotted lines in (a) and (b) are scattered intensity profiles; in plots (c) and (d) the solid lines are descattered intensity profiles and the dotted lines are intrinsic intensity profiles for comparison; and the plots of (e), (f) and (g) are scattered, intrinsic and descattered PPA curves, respectively.

pulse profiles and PPA curves. The intensity profiles are normalized to their own peak intensity, and the error of the PPA is calculated the same as in von Hoensbroech & Xilouris (1997) by

$$\Delta \psi = \frac{\sqrt{(Q \cdot \mathrm{rms}_U)^2 + (U \cdot \mathrm{rms}_Q)^2}}{(2L^2)}.$$
(14)

In all Figures from 2–6, the solid lines in the plots are the recovered total intensity (c) and linear intensity profiles (d), the dotted lines in (a) and (b) are scattered total intensity profiles (upper panel) and linear intensity profiles (lower panel), the dotted lines in (c) and (d) are total intensity (upper panel) and linear intensity (lower panel) profiles of intrinsic pulse profiles for comparison, and the plots on the bottom are scattered PPA curves (upper panel (e)), PPA curves of intrinsic pulse signals (upper panel (f)) and recovered PPA curves (lower panel (g)). " $5\Delta\psi$ " error bars are presented in all the figures of the (e), (f) and (g) plots.

For PSR B1356–60, in Figure 2 the descattered pulse profiles and PPA curve observed at 0.659594 GHz are shown, and the intrinsic pulse profile is observed at 1.56 GHz. All three models are tested and they produce similar results. The application of the thick screen model is presented here, and the recovered intensity pulse profiles (c), (d) and the PPA curve (g) are similar to those of the intrinsic pulse signal.

For PSR B1831–03, in Figure 3 the descattered pulse profiles and PPA curve observed at 0.4 GHz are shown, and the intrinsic pulse profile is observed at 0.61 GHz. All three models have been tested, and they produce similar results with different scattering time scales. The application of the thin screen model is given here, and the total intensity and linear intensity profiles match well with those of the intrinsic pulse profiles. The recovery of a PPA curve results in a jump-like feature in itself.

For PSR B1838–04, Figure 4 demonstrated a recovered pulse intensity profile and PPA curve observed at 0.606 GHz, and the intrinsic pulse profile is observed at 0.925 GHz. All three models have been checked, and the extended and thick screen models produce the same intensity profile and PPA curve results; they produced flat PPA curves. Here the thin screen model has been applied, and the recovered intensity profiles do not match very well with the intrinsic profile, but the PPA curve shows an S-curve-like feature (Lorimer & Kramer 2005). In this pulsar, another high frequency profile observed at 1.4 GHz was tried for comparison with the recovered pulse profile, but results were not good.

For PSR B1859+03, Figure 5 plots the descattered pulse profiles and the PPA curve is observed at 0.606 GHz, and the intrinsic pulse profile is observed at 0.925 GHz. All three models are tried and all of them worked well. The intensity profiles and PPA curves all have the same features. The presented plots in Figure 5 are obtained by using the thin screen model. The recovered intensity profiles are similar to the intrinsic profiles, and the PPA curve (g) is much the same as the PPA curve (f) of the intrinsic one.

For PSR B1946+35, Figure 6 gives the descattered pulse profiles and the PPA curve is observed at 0.408 GHz; the intrinsic pulse profile is observed at 0.61 GHz. All three models are tested, and all the models give good results. In the extended screen model, the PPA curve shows a flat pattern, and in the other two models the PPA curves show a jump-like structure. Shown here is the application of the thick screen model. The recovered pulse profiles are quite similar to the intrinsic pulse profiles, and the recovered PPA curve shows a jump-like feature as shown in Figure 6. It is acceptable to add 90 degrees to the last four points of curve (g) (Jaroenjittichai & Kramer 2009), making the PPA curve much like the positive part of plot (f). Interestingly, the higher frequency observation of 0.925 GHz, at 1.408 GHz, shows orthogonal jumps in its PPA curve (Lorimer et al. 1998), which indicates that the recovered PPA curve (g) may be plausible. A fuller discussion will be presented in the next section.



Fig.4 PSR B1838-04. The dotted lines in (a) and (b) are scattered intensity profiles; in plots (c) and (d) the solid lines are descattered intensity profiles and the dotted lines are intrinsic intensity profiles for comparison; and the plots of (e), (f) and (g) are scattered, intrinsic and descattered PPA curves, respectively.

4 DISCUSSION

Section 3.1 showed the simulation of scattering and descattering results, and as indicated in Figure 1, the scattering can cause pulse broadening and flattening of the PPA curve. When there is a jump in the PPA in the original pulse after scattering, the PPA curve can be much more complicated, but the PPA curve can be descattered as shown in plots (f) and (l). In Section 3.2, which is devoted to practical applications, the intensity pulse profiles and PPA curves of five pulsars have been descattered, and in each pulsar the frequency of the intrinsic pulse profile for comparison is below 1.4 GHz. In almost all pulsars the recovered profiles and the PPA curves are quite similar to the features of the intrinsic pulse profiles and 6). These results in Section 3.2 support the previous assumption that the original pulse characteristics are substantially frequency-invariant below 1.4 GHz (Radhakrishnan & Cooke 1969).

When carrying out the descattering process, the existence of pulse width evolution following changes in frequency has been ignored (Lorimer & Kramer 2005) because of the small difference in frequency between the scattered pulse profiles and the intrinsic pulse profiles.



Fig. 5 PSR B1859+03. The dotted lines in (a) and (b) are scattered intensity profiles; in plots (c) and (d) the solid lines are descattered intensity profiles and the dotted lines are intrinsic intensity profiles for comparison; and the plots of (e), (f) and (g) are scattered, intrinsic and descattered PPA curves, respectively.

Figures 2-6 show that all the descattered compensations to the scattered pulse profiles are good, except for the intensity pulse profiles of PSR B1838-04 (see Fig. 4). This may arise from the roughness of the scattered pulse profiles. In PSR B1356-60, the frequency of a chosen intrinsic pulse profile for comparison is 1.56 GHz, because no other observed frequencies are available below 1.4 GHz. The recovered PPA curves in all pulsars also showed good agreement with our expectations, namely that some of them have similar features to their intrinsic PPA curve (see Figs. 2 and 5). The PPA curve in Figure 4 shows an S-curve-like feature, and some of them have jump-like features (see Figs. 3 and 6). The jumps in Figures 3 and 6 can be understood through the simulation in Section 3.1. If the original PPA curve has jump features which were distorted or flattened by scattering (Karastergiou 2009), the recovery of such a PPA curve is likely the cause of jumps within a true scattering model. Fortunately, in the higher frequency observations of 0.9 GHz and 1.4 GHz for pulsar B1946+35 showed orthogonal jumps in their PPA curves (Lorimer et al. 1998). These are the intrinsic pulse profiles compared to the scattered pulse profile observed at 0.408 GHz. The jumps observed are much more likely to be the intrinsic character of the PPA curves of this pulsar's signal, which can be observed below 1.4 GHz. According to the simulation, observational evidence and the empirical assumption of frequency invariance of pulse characters below 1.4 GHz (Radhakrishnan



Fig. 6 PSR B1946+35. The dotted lines in (a) and (b) are scattered intensity profiles; in plots (c) and (d) the solid lines are descattered intensity profiles and the dotted lines are intrinsic intensity profiles for comparison; the plots of (e), (f) and (g) are scattered, intrinsic and descattered PPA curves, respectively.

& Cooke 1969), it can be said that the occurrence of jumps in our descattering compensation of the PSR B1946+35 is acceptable, and would be the intrinsic feature of the scattered PPA curve observed at 0.408 GHz. For pulsar B1831-3, there is no observational result for the PPA curve with an orthogonal jump in the EPN database, so it may be easier to explain when adding 90 degrees to the last five points.

5 CONCLUSIONS

We have shown the descattering compensation for the pulse profiles and PPA curves of five pulsars, and the compensation for scattered pulse profiles and PPA curves brought us good results. Through simulation and practical application, it is found that all the intrinsic characteristics of pulse signals can be recovered if the scattering model is clear enough. The recovery of pulse characteristics is an important issue in pulse study and rotation measurement (RM), and in setting the arrival time of impulse signals from pulsars. The recovered S-curve-like PPA curves of a pulsar such as B1838–04 would give us an opportunity to apply the RVM (Radhakrishnan & Cooke 1969) to set the magnetic inclination angle α and impact parameter β . In a word, the recovery of pulse profiles and PPA curves may improve our understanding of pulse emission regions and emission mechanisms. In this paper,

three Stokes parameters, I, Q and U, have been restored. The Stokes parameter V has been left for later discussion. We hope to continue studying the Stokes phase portraits (Chung & Melatos 2011) of the five pulsars, and this may be useful for research in pulsar emission properties.

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