

Improving pulsar distances by modelling interstellar scattering

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ABSTRACT

We present here a method to study the distribution of electron density fluctuations in pulsar directions as well as to estimate pulsar distances. The method, based on a simple two-component model of the scattering medium discussed by Gwinn, Bartel & Cordes, uses scintillation and proper motion data in addition to the measurements of angular broadening and temporal broadening to solve for the model parameters, namely, the fractional distance to a discrete scatterer and the associated relative scattering strength. We show how this method can be used to estimate pulsar distances reliably, when the location of a discrete scatterer (e.g. an H II region), if any, is known. Considering the specific example of PSR B0736–40, we illustrate how a simple characterization of the Gum nebula region (using the data on the Vela pulsar) is possible and can be used along with the temporal broadening measurements to estimate pulsar distances.

Key words: scattering – stars: distances – stars: kinematics – pulsars: general – ISM: general – H II regions.

1 INTRODUCTION

Reliable estimation of pulsar distances forms a crucial input for many important investigations of pulsar properties, particularly those concerning spatial distribution, space velocities, birth-rates, etc. The conventional method for estimation of distances is based on the measured value of the column density of electrons between ourselves and the pulsar (i.e. the dispersion measure, DM) combined with our assumption of the distribution of free electrons in the Milky Way. Other methods, which give the so called *independent distance estimates*, are based on pulsar association with a supernova remnant (or a globular cluster), measurements of annual parallax for nearby pulsars or the useful limits through H I absorption measurements (possible for pulsars in the galactic plane). These ‘independent’ estimates provide important constraints for models describing the distribution of electron density in our galaxy.

Although the model of the electron density distribution based on pulsar data has received many refinements over the years (e.g. Prentice & ter Haar 1969; Vivekanand & Narayan 1982; Lyne et al. 1985), the recent comprehensive model by Taylor & Cordes (1993) represents a major qualitative improvement wherein the spiral-arm structure has been incorporated explicitly. This model is derived based on the H II region distribution, constraints provided by the ‘independent’ estimates of distances, data on scatter broadening of pulsar signals, the radio continuum emission associated with our galaxy, etc. Estimation based on this model (and using the disper-

sion measures of pulsars) has pushed pulsar distances farther by a factor of 1.5 to 2 compared to earlier similar estimates, particularly for the ‘local’ pulsars. This has had a serious implication in terms of a corresponding increase in the estimated velocities of pulsars based on the measured proper motions.

Although this model is a considerable improvement, some features are worth noting. The typical uncertainty in most of the available estimates is believed to be about 20–30 per cent (rms), while in some cases, distances are uncertain by a factor of 2 or more. For example, the model is seen to over-estimate by a large factor (in some cases > 2) the distances to pulsars at high Galactic latitudes. An analysis of the correlation of the pulsar distribution with the spiral arm locations (Ramachandran & Deshpande 1994) points out a possible bias in the estimated pulsar locations towards the spiral arms. This bias could be understood in terms of a possible under-estimation of the electron density in the interarm regions. If this is true, then we estimate that the use of the Taylor & Cordes model leads to an over-estimation of distances (using DMs) by 30 per cent or so for the local population of pulsars.

In light of these, the need for a more reliable distance estimator for pulsars cannot be over-emphasized. In this paper, we explore an attractive possibility wherein the observables associated with the interstellar scattering can be used in the distance estimation.

The fluctuation of the electron density in the interstellar medium gives rise to a variation of the refractive index, which results in the scintillation of radio signals. The basic analysis of scintillations in terms of these refractive index fluctuations was presented by Scheuer (1968). Over the years, many authors have studied this problem in detail, and have shown that scattering introduces many

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other observable effects like apparent angular broadening, temporal broadening, intensity scintillations, etc. (Scheuer 1968; Rickett 1969; Alcock & Hatchett 1978; Goodman & Narayan 1985; Blandford & Narayan 1985).

On the whole, the distribution of scattering material in the Galaxy can be represented by high-density localized components associated with H II regions and supernova remnants, and a more diffuse uniformly distributed component. Gwinn, Bartel & Cordes (1993) discuss in detail how the angular broadening and the temporal broadening of the pulsar signal can be effectively used to study the distribution of scattering material along the line of sight. In this paper, we extend this idea by introducing two more observable parameters, the diffractive scintillation time-scale t_{dif} and the proper motion μ , and present a method for distance estimation using the various observables along with some possible knowledge about the distance to the scatterer.

Sections 2 and 3 present some basic relations that form the essence of the paper, connecting angular broadening of sources, interstellar scintillation time-scales, and other parameters assuming a reasonably general two-component description for the scattering material. In Sections 4 and 5, we discuss how this formulation can be used to estimate distances to pulsars, and, in turn, to study the distribution of electron density fluctuation in the interstellar medium. Particularly, as we describe, this method can be used to probe and model regions of enhanced scattering like the Gum Nebula, the Cygnus OB complex, etc.

We also discuss the specific case of PSR B0736–40, in Section 6, where the recent measurement of temporal broadening (Ramachandran et al. 1997) has shown excess scattering attributable to the Gum Nebula. We estimate the distance to this pulsar to be ~ 4.5 kpc, far less than the distance of > 11 kpc derived on the basis of the model by Taylor & Cordes (1993), reducing significantly the derived velocity of this pulsar.

2 APPARENT ANGULAR BROADENING

The rms angular broadening of a source at a distance D from the observer is given by (Alcock & Hatchett 1978; Blandford & Narayan 1985)

$$\theta^2 = \frac{1}{D^2} \int_0^D z^2 \psi(z) dz, \quad (1)$$

where z is the line-of-sight distance coordinate, the value of which is zero at the location of the pulsar, and D at the observer. $\psi(z)$ is the mean scattering rate per unit length. This rms broadening is related to the FWHM diameter θ_{H} of the source by $\theta_{\text{H}}^2 = (4 \ln 2) \theta^2$.

The mean temporal broadening of the pulse profile is given by (Blandford & Narayan 1985)

$$\tau_{\text{sc}} = \frac{1}{2cD} \int_0^D z(D-z) \psi(z) dz. \quad (2)$$

The mean temporal broadening is related to the decorrelation bandwidth ($\Delta\nu$) by the uncertainty relation: $2\pi\tau_{\text{sc}}\Delta\nu = 1$. As indicated by the above two equations, the angular broadening of the source is maximum when the scatterer is close to the observer, and the temporal broadening is maximum when the scatterer is located mid-way along the line of sight. Now, let us assume that the distribution of scattering material in a given line of sight can be adequately described by two components: a uniformly distributed component, and a thin screen located at a distance of xD from the observer. With this assumption, the relations in equations (1) and (2)

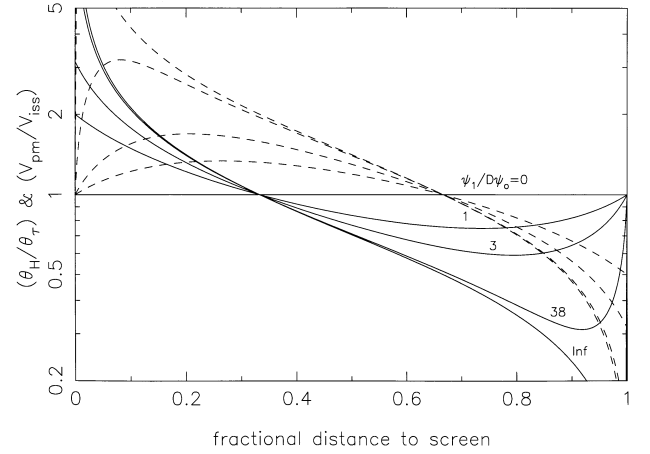


Figure 1. The behaviour of the two ratios R_θ (solid line; equation 6) and R_τ (dashed line; equation 10) as function of x and $\psi_1/D\psi_0$.

can be expressed as (Gwinn et al. 1993)

$$\theta_{\text{H}}^2 = 4 \ln 2 \frac{D\psi_0}{3} \left[1 + 3(1-x)^2 \frac{\psi_1}{D\psi_0} \right]$$

$$\tau_{\text{sc}} = \frac{D}{4c} \frac{D\psi_0}{3} \left[1 + 6x(1-x) \frac{\psi_1}{D\psi_0} \right]. \quad (3)$$

Here, ψ_1 & $D\psi_0$ give the mean scattering rate for the discrete *thin* screen and the uniform component, respectively. In practice, measuring the angular broadening of a source requires observations using very long-baseline interferometry. In principle, it is possible to estimate the amount of angular broadening from the measured value of the temporal broadening, if we have the knowledge of the distribution of scattering material along the line of sight. In the absence of such knowledge, a simple-minded estimate of the angular broadening (θ_τ) is possible and can be obtained as

$$\theta_\tau^2 = 4 \ln 2 \left(\frac{4c\tau_{\text{sc}}}{D} \right) \quad (4)$$

Although such a simple-minded estimate was originally suggested for a case of thin scatterer midway between the pulsar and the observer, the constant in the above expression (which comes through the definition of τ_{sc} in equation 2) is such that the θ_τ and the θ_{H} would match in the case of a uniformly distributed scatterer. With this, and given the different dependences of the two estimates of θ on x , this expression gives an estimate that matches θ_{H} even when a thin scatterer is included at $x = (1/3)$. Also note, that at $x = (1/3)$, the ratio of θ s becomes independent of the relative strengths of scattering for the two components (see Fig. 1). Thus, for consideration of the θ ratio, a uniformly distributed scatterer can be replaced by an equivalent thin scatterer at $x = (1/3)$ and vice versa. Using the expression for τ_{sc} and the above relation, we have

$$\theta_\tau^2 = 4 \ln 2 \frac{D\psi_0}{3} \left[1 + 6x(1-x) \frac{\psi_1}{D\psi_0} \right]. \quad (5)$$

Note that θ_τ is not equal to θ_{H} in general. The difference depends on the values of x and $\psi_1/D\psi_0$. Let us define a parameter $Y = (\psi_1/D\psi_0)$. This parameter is the ratio of the mean scattering strength of the thin screen and the distributed component. The ratio of the measured angular broadening (θ_{H}) and the estimated value (i.e. θ_τ) is given by (Gwinn et al. 1993)

$$R_\theta = \frac{\theta_{\text{H}}}{\theta_\tau} = \left[\frac{1 + 3(1-x)^2 Y}{1 + 6x(1-x) Y} \right]^{1/2} \quad (6)$$

Depending on the validity of the assumption that the scattering material is uniformly distributed along the line of sight, this ratio will deviate from unity.

This relation has been derived and used by Gwinn et al. (1993) to infer values of x along sight-lines to a few pulsars. However, they use the available estimates of pulsar distance as an input in the analysis. In the approach we wish to advance, we would like to invert this problem to solve for the distance to a pulsar, given the distance to the discrete scatterer. To be able to do so, we need to know the values for $(\psi_1/D\psi_0)$ and the scatterer distance $d_s (= xD)$. While in many cases it may be possible to identify a discrete scattering region along a pulsar sight-line and use the known distance to such a region, the contrast in the scattering rate Y remains as one more ‘unknown’, unless this ratio can be assumed to deviate from unity by a large factor. In the next section, we identify another similar but independent relation which allows us to in fact also solve for the value of Y .

3 TRANSVERSE VELOCITIES

The pulsar velocities inferred from the observed decorrelation time-scales of interstellar scintillations compare well, on the average, with those estimated from proper motion measurements (Cordes 1986; Gupta, Rickett & Lyne 1994). The reason for possible disagreements in the values estimated in these two ways is often attributable to the breakdown of the assumption regarding the distribution of the scattering medium along the sight-line. Gupta et al. (1994) give the relevant expressions for the case of a single thin screen. In this section, we derive a general expression for this comparison, in terms of x , D , and $(\psi_1/D\psi_0)$, for a two-component model.

The diffractive scintillation time-scale associated with a screen at a location x from the observer and having a characteristic irregularity size a , can be expressed as

$$t_{\text{dif}}(x) = \left[\frac{x\lambda D}{\pi a v_f} \right] = \left[\frac{\lambda(1-x)}{\pi \theta v_{\text{pm}} x} \right] \quad (7)$$

where λ is the observing wavelength, v_f is the apparent velocity of the scintillation pattern across the observer, and v_{pm} is the transverse velocity of the pulsar (which can be estimated from proper motion measurements). It is easy to show, that the effective t_{dif} value corresponding to the distributed scattering material is related to the harmonic mean of the t_{dif}^2 values for each of the sub-screens at different values of x . For our two-component model, the apparent t_{dif} can be expressed as

$$\begin{aligned} \frac{1}{t_{\text{dif}}^2} &= \frac{\pi^2 v_{\text{pm}}^2}{\lambda^2 D^2} \int_0^D x^2 \psi(x) dx \\ &= \frac{\pi^2 v_{\text{pm}}^2 D \psi_0}{\lambda^2} \left[1 + 3x^2 Y \right]. \end{aligned} \quad (8)$$

With the knowledge of the measured values of τ_{sc} and t_{dif} the transverse velocity (v_{iss}) of the pulsar can be estimated as (Cordes 1986; Gupta et al. 1994)

$$v_{\text{iss}}^2 = \frac{Dc}{4\pi^2 \tau_{\text{sc}} t_{\text{dif}}^2 \nu^2}, \quad (9)$$

where ν is the observing frequency. With equations (3) and (8), the above equation can be rewritten to define the ratio $v_{\text{pm}}/v_{\text{iss}}$ as

$$R_v = \frac{v_{\text{pm}}}{v_{\text{iss}}} = \left[\frac{1 + 6x(1-x)Y}{1 + 3x^2 Y} \right]^{1/2}. \quad (10)$$

In the above discussion, we have ignored the contribution to the

observed t_{dif} owing to the observer’s motion and the possible motion associated with the medium. However, the observed t_{dif} can be corrected for these in cases where these contributions are significant. It is also worth mentioning that we have carefully examined the definitions of the relevant observables and the constants in all of the above equations. Using detail simulations we have verified them to be consistent with those used by Gupta et al. (1994).

4 ESTIMATION OF DISTANCES

Fig. 1 shows the behaviour of the two ratios R_θ and R_v (equations 6 and 10) as a function of the fractional distance x to a discrete scatterer (from the observer) and the associated relative strength of scattering Y . Solid lines are for the ratio R_θ , and the dash lines for R_v . Note that, except when $Y = 0$, the two ratios deviate from unity in general. It is easy to see that, though the two ratios, R_θ and R_v , show relative behaviour that is anti-symmetric around $x = 0.5$, they do provide two independent relations between the quantities of interest. Hence, these relations can be used together to estimate the distance to a pulsar as well as the relative strength of scattering Y if the discrete scatterer distance ($d_s = xD$) is known.

The four observable quantities necessary for this purpose are, (i) the apparent angular broadening θ_H , (ii) the temporal broadening of the pulse profile τ_{sc} , (iii) the diffractive scintillation time-scale t_{dif} , and (iv) the proper motion v_{pm} . While these depend on the pulsar distance, the two ratios R_θ and R_v (see equations 6 and 10) are independent of the pulsar distance. However, in practice, the estimation of these two ratios based on the four observables involves assumption of a distance, since $\theta_r \propto \sqrt{1/D}$, $v_{\text{pm}} = \mu D$, and $v_{\text{iss}} \propto \sqrt{D}$, such that both the ratios have \sqrt{D} dependence.

Let us therefore express $R_\theta^2 = D r_\theta^2$, and $R_v^2 = D r_v^2$, where r_θ and r_v can be treated as the estimated values of R_θ and R_v respectively if D were to be equal to 1 kpc. Then, by using equations (6) and (10), and eliminating $(\psi_1/D\psi_0)$, we get a useful relation between D and x , as

$$D^2 r_\theta^2 r_v^2 (2x - 3x^2) + D r_v^2 (2x - 1) + (3x - 1)(x - 1) = 0. \quad (11)$$

Another independent relation, $d_s = xD$, would be obvious, once the distance to the discrete scatterer is known. With these equations, the distance to the pulsar can be estimated, once we know the distance to the thin screen scatterer and the ratios r_θ, r_v .

As we will discuss later in this paper, it may be possible to ascertain the distance to a possible discrete scatterer in many cases. However, as mentioned above, estimation of these two ratios is possible only if all the four parameters are measured. Though the measurement of t_{dif} and τ_{sc} is more easy to come by, the measurement of the other two quantities involves very long-baseline interferometry and therefore, the required measurements are available for only a few pulsars. For instance, angular broadening measurements exist for only a handful of pulsars (Gwinn et al. 1993). Reliable measurements of θ_H and μ are available so far for only one pulsar, namely the Vela pulsar. At 2.3 GHz, the measured values of the scattering parameters are, $\theta_H = 1.6 \pm 0.2$ mas, $t_{\text{dif}} = 15$ s, and the decorrelation bandwidth is 68 ± 5 kHz (Desai et al. 1992). The measured proper motion is 59.4 ± 2 mas yr⁻¹ (Bailes et al. 1990). Based on these, the corresponding values of r_θ and r_v are 0.49 kpc^{-1/2} and 0.96 kpc^{-1/2}, respectively.

The solid line in Fig. 2 shows the relation in equation 11 after using these ratios. The dashed line in the figure corresponds to the relation $D = (d_s/x)$, where d_s , the distance to the discrete scatterer is assumed to be equal to 400 pc. Although this is one of the estimates

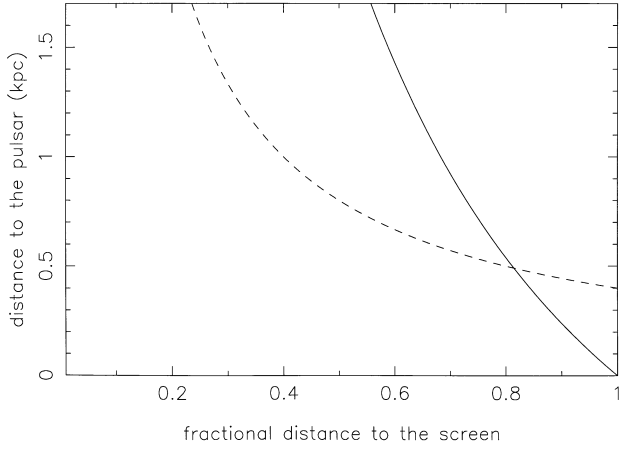


Figure 2. Estimation of distance to Vela pulsar. Solid line gives the relation between x and D according to equation (11) (with $r_\theta = 0.49 \text{ kpc}^{-1/2}$ and $r_v = 0.96 \text{ kpc}^{-1/2}$), and the dashed line is for $D = (d_s/x)$ using $d_s = 400 \text{ pc}$.

of the estimates for the scatterer distance by Desai et al. (1992), our assumption is based on the following independent argument. According to the Taylor & Cordes (1993) model for the electron density distribution, the Gum Nebula is modelled at a distance of about 500 pc with a radius of about 180 pc. Thus, the mean distance of the section of the Gum nebula that may be in the foreground of the Vela pulsar would be in the range 300–500 pc. Hence, we consider the relevant mean distance to be nominally 400 pc. The intersection of these two curves in Fig. 2 represents the solution in terms of x and D . In the present case, the intersection is at $x = 0.8$ and $D = 500 \text{ pc}$, which agrees with the generally accepted distance to the Vela pulsar. As can be seen from the solid-line curve in Fig. 2, that an uncertainty of the order of 100 pc in the scatterer distance will imply very small change in the fractional distance (x). So the distance to the Vela pulsar would be $500 \pm 125 \text{ pc}$ considering the worst case error. As we shall see in a following section, an independent estimation of the distance the Vela pulsar (see Table 1) also supports our assumption of the scatterer distance, remembering that the fractional distance is about 0.8.

It is worth recalling here that Desai et al. (1992) also derive an effective fractional distance of 0.81 ± 0.03 , by however assuming a 500 pc distance to the Vela pulsar (Frail & Weisberg 1990), implying an effective distance of 400 pc to the scatterer. However, Desai et al. argue that, since the near-edge of the Gum Nebula is at about 270 pc (Sivan 1974; Reynolds 1976), the scattering observed in Vela pulsar cannot be as a result of the Gum nebula. When they consider a uniformly distributed scattering component with strength close to the Galactic disc (Cordes, Weisberg & Boriakoff 1985), then the fractional distance to the scatterer turns out to be $x = 0.87$. Alternatively, they argue that, if the Gum nebula scatters intrinsically as much as 5 per cent as strongly as the other scattering screen, then the screen is pushed to a fractional distance of $x = 0.95$. However, we have assume an effective fractional distance of 400 pc as the distance to the scatterer and, by our independent method, we find a solution the x to be equal to 0.8, implying the distance to the Vela pulsar as 500 pc. In the framework of our present two-component model, our results are in excellent agreement with those by Desai et al. (1992).

5 DESCRIPTION IN THE $(v_{PM}/v_{ISS})-(\theta_H/\theta_r)$ PLANE

Although, in practice, the above procedure is convenient to use, it is

Table 1. Distances (for B0736–40 and the Vela pulsar) estimated by changing the electron density for the Gum nebula component in the model of Taylor & Cordes (1993), and the corresponding fluctuation parameter implied by the observed temporal broadening. The first column gives the ‘enhancement factor’ for the assumed electron density, the second and fourth columns give the values of the fluctuation parameter and the third and the fifth columns give the corresponding distances in the two cases.

n $\times 0.2 \text{ cm}^{-3}$	0736–40		Vela pulsar	
	f	D (kpc)	f	D (kpc)
1.0	15.3	11.0	7.3	0.61
1.1	12.8	11.0	7.0	0.59
1.2	10.6	9.1	6.85	0.57
1.3	8.75	7.1	6.75	0.55
1.4	7.45	5.9	6.6	0.53
1.5	6.40	5.1	6.5	0.52
1.6	5.65	4.4	6.4	0.51
1.7	5.00	3.8	6.3	0.50
1.8	4.45	3.3	6.3	0.49
1.9	4.00	2.9	6.2	0.48
2.0	3.65	2.5	6.2	0.48

instructive to express the dependences of the two ratios R_θ and R_v on x and $\psi_1/D\psi_0$ in a general form as shown in Fig. 3. The two sets of curves indicated by the continuous and the broken (dashed) lines correspond to different constant values of $Y = (\psi_1/D\psi_0)$ and x respectively. The dot (with the error bars) represents the data on the Vela pulsar using the above derived distance. The relative scattering strength Y of the discrete scatterer, as seen from the diagram, is very high as would be expected from the known anomalous scattering in this direction.

Given the measurements of the four required observables, the possible combinations of D , x and Y can be represented on this log–log plot by a straight line of 45° slope parallel to the line corresponding to $Y = \infty$. Each point on such a line will correspond to a distinct value of the pulsar distance (depending on r_θ , r_v), and in general, would imply a unique combination of x and Y . The *correct* distance would correspond to one such point, for which the implied value of x is consistent with our knowledge of d_s .

There are some *prohibited areas* in this diagram, namely, the lower-right square ($R_\theta > 1 > R_v$) and the upper-left triangle ($r_v/r_\theta > 2$). For example, the range of distances corresponding to the sections through the lower-right square can be rejected. When such a rejectable range is large, it would imply that the discrete scatterer is dominant and that it is quite close to either the pulsar or the observer. In such cases, some other rather simple considerations may be enough to yield useful limits on the pulsar distance. On the other hand, the ‘impossibility’ of $r_v/r_\theta > 2$ in the present two-component model, may be utilized to constrain the values of some of the observables that may not be known or have large uncertainties. Similar considerations would also apply for the other ‘prohibited’ square region.

In certain cases, when it is possible to assume absence of any discrete component of enhanced scattering along a sight-line, the region of interest is confined to the central part of the diagram that is bounded by, say, $Y = 0.5$. This makes it possible then to estimate the pulsar distance within an uncertainty of 20 per cent or so, even when only one of the two ratios, r_θ or r_v , may be known. It is worth remembering that in such cases the parameter x is not important.

In certain other cases, it may be clear that a discrete screen is the dominant scatterer (e.g. like the Gum nebula in the case of the Vela

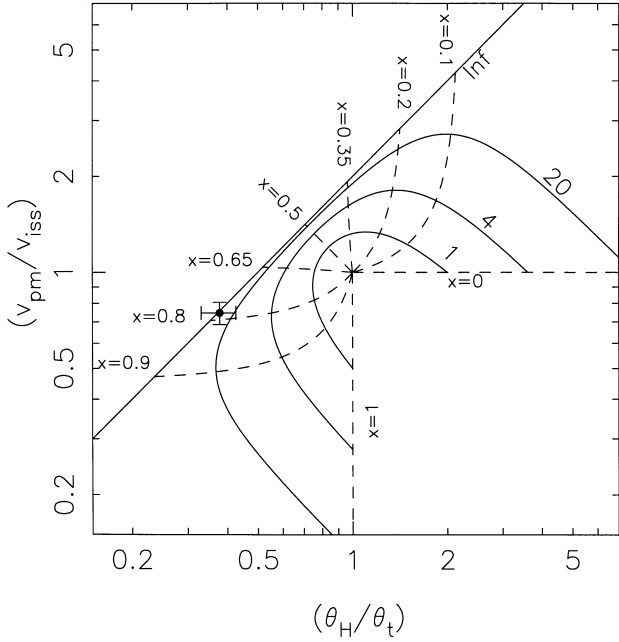


Figure 3. A combined description of the dependences of the ratios R_θ and R_v on x and $Y (= \psi_1/D\psi_0)$ corresponding to the two-component model for scattering. The solid and the dashed curves show the relation between the two (velocity and the angular size) ratios for different constant values of Y and x respectively. The dot and the error bars correspond to the data on the Vela pulsar. (See text for more details.)

pulsar). Then, the relation in equation (11) can be approximated to assume simple forms where the ratios r_θ and r_v can be decoupled. The two resultant relations can then be expressed in terms of d_s , as

$$x = 1 - 2d_s r_v^2 \quad \text{or} \quad x = 1 - \frac{1}{2}d_s r_\theta^2. \quad (12)$$

In this regime, the fractional distance x and the pulsar distance can be estimated reasonably accurately even when only one of the ratios is known, provided the ‘true’ value of x is not very small (i.e. not < 0.1). Otherwise, both the ratios need to be known so as to avoid a large error in the distance estimation. In general, the low–low and the high–high combinations of the R_θ, R_v values [as also when (R_θ/R_v) is nearly equal to 2] definitely indicate the presence of a dominant discrete scatterer. Therefore, when the presence of a dominant discrete scatterer can be assumed, this connection between R_θ and R_v can be exploited suitably when only one of two ratios is known, and the other ratio is required to be estimated.

It is easy to note from the diagram (as also from equation 11) that the distance estimation becomes independent of one of the two ratios (r_θ or r_v) when $x=0$, $(1/3)$, $(2/3)$ or 1, while that ratio will be important only for the determination of Y . A nearly similar behaviour is also evident when $Y \gg 1$. For example, the distance determination would be less sensitive to uncertainties in R_θ (R_v) when $x > (2/3)$ [$x < (1/3)$]. This should dictate the choice of the measurement and the corresponding relation to be used (of the two in equation 12, for example) for determining x and D .

This diagram thus provides us a useful and a nearly complete description in terms of the dependence of the two observable ratios on the two model parameters x and Y , which represent the fractional distance and the relative strength of scattering respectively for the discrete scatterer in the assumed two-component model.

6 ANOMALOUS SCATTERING AND DISTANCE TO PSR B0736–40

In some cases, a dominant discrete scatterer may be common to sight-lines to a number of pulsars. In such a case, characterization of the scattering region can be attempted using the data on the four observables which may be available for only a few pulsars and the results could be used in determining distances to the other pulsars with nearby sight-lines. This relaxes the requirement that all four observables be available for the rest of the pulsars in the set and, in fact, the knowledge of DM and temporal scatter broadening alone suffices for distance determination. We illustrate this possibility by considering the Gum nebula region as a common scatterer for a number of pulsar sight-lines.

Taylor & Cordes (1993) do include the enhanced electron density in the Gum nebula region in their model, but state that the modelling of this component is far from complete since a proper modelling would require many more constraints (for both the dispersion and the scattering) than are presently available. They have, therefore, assumed the fluctuation parameter (which quantifies the amount of scattering in the medium, given the value for the electron density) associated with the Gum nebula to be equal to *zero*. In the following part of this section, we show that the data on the Vela pulsar can be exploited to *calibrate* this fluctuation parameter (as defined in the Taylor & Cordes model).

In a simple exercise, we varied the assumed number density and the fluctuation parameter associated with the Gum nebula in the framework of the Taylor & Cordes model to obtain values of these parameters that would be consistent with the known DM (69 pc cm^{-3}) and τ_{sc} (8.25 ms at 327 MHz) as well as the derived distance (500 pc) to the Vela pulsar. As shown in Table 1 (columns 1, 4 and 5), the electron density in the Gum nebula region needs to be about 60 per cent higher than that suggested in the Taylor & Cordes model. The value of the fluctuation parameter is about 6.3, close to that for the spiral arm component in the Taylor & Cordes model. Although the Gum nebula is quite complicated in its structure and morphology, it may not be unreasonable to assume that the above estimates would be more or less valid for other sight-lines through the Gum region.

With this view, we consider another pulsar B0736–40 ($l = 254^\circ.2$, $b = -9^\circ.2$ and $\text{DM} = 160.8 \text{ pc cm}^{-3}$), for which the estimated distance on the basis of the Taylor & Cordes (1993) model is $> 11 \text{ kpc}$ (and therefore would be placed beyond the ‘outer’ spiral arm). As part of our survey (in 1996) to measure the temporal broadening of pulse profiles at 327 MHz (Ramachandran et al. 1997), we observed this object and measured the temporal broadening to be $76 \pm 3 \text{ ms}$. Assuming the excess scattering is owing to the Gum nebula, we again seek a combination of the electron density and the fluctuation parameter that would be consistent with the DM and τ_{sc} values, and the distance estimate associated with it. As can be seen from Table 1, both the cases, the Vela pulsar and B0736–40, are consistent with the electron density and the fluctuation parameter values of 0.32 cm^{-3} and ~ 6.3 respectively. This, therefore, allows us to derive a distance to B0736–40 as $\sim 4.5 \text{ kpc}$ (with an uncertainty of about 0.8 kpc) based on our measurement of the temporal broadening and the *calibration* from the Vela pulsar data.

We also find that the excess temporal broadening cannot be accounted for by even a large increase in the electron density associated with the ‘outer’ spiral arm component. The z -height of about 700 pc , based on our new estimate, implies that the ‘true’ distance could be even shorter given the possibility that the effective

scaleheight of the electron distribution may be somewhat underestimated in the Taylor & Cordes model. As one of the important implications of this distance determination, the estimated velocity of the pulsar would now be less than 1600 km s^{-1} (using a proper motion of about 72.5 mas yr^{-1}) rather than a value $> 3780 \text{ km s}^{-1}$ as was implied by the earlier distance estimate.

Any more detailed modelling of the distribution of electron density and its fluctuation across the Gum nebula region is beyond the scope of this paper, and needs new measurements of scattering parameters of a number of pulsars that could be behind this region. We, however, have shown how distance estimates for many such pulsars could be refined already with the help of the scatter broadening measurements.

7 DISCUSSION AND CONCLUSIONS

We have described in this paper a method to study effectively the distribution of the electron density fluctuations in the interstellar medium by assuming a simple model that seems consistent in most cases. Essentially, suitable combinations of four measurable quantities for pulsars, namely the temporal broadening of pulse profiles, angular broadening of the source, diffractive scintillation time-scale, and the proper motion, allow us to solve for the parameters of the scatterer as well as for the pulsar distance. The important simplifying assumption that has gone into this analysis is that the scattering along the sight-line can be adequately modelled in terms of just two components, a thin screen scatterer and a uniformly distributed component. It is clear that for lines of sight which pass through, say, two spiral arms, this simple picture would need to be modified. However, for a large number of pulsars, our present assumption can be justified (Gwinn et al. 1993). One would naturally attempt to model the local medium first and use that knowledge while probing progressively the farther section. In such a case, it is easy to see that the number of *unknowns* in the problem at any stage would not be too many to handle.

One of the important ingredients in our method is the knowledge of the distance to the discrete scatterer, particularly if such a scatterer is the dominant source of scattering. For most nearby pulsars (within 2 kpc or so) such a scatterer, if any, should be identifiable as an H II region or the Stromgren region of some OB stars or as a region associated with a supernova remnant. It is therefore reasonable to assume that, in most such cases, the scatterer distance would be available (see, for example, Prentice & ter Haar, 1969). For pulsars at high galactic latitudes, it may be possible to assume that the dominant scatterer is at a z -height defined by the scaleheight of the H II region distribution in the disc of the galaxy. For somewhat distant pulsars well within the disc, the discrete scatterer may be identifiable with a spiral arm component. (In such cases, the distance limits that may be available from H I absorption measurements can be incorporated in the analysis as additional constraints.) We therefore do not consider the scatterer distance as a difficult ingredient to supply.

The method we have proposed can therefore be used for reliable determination of distances to a large number of pulsars as well as for probing a usefully large volume of the galaxy for its electron density distribution. A systematic and intensive observational program to

measure the scattering effects and proper motions of pulsars would be extremely fruitful. In cases with dominant discrete scatterers, it may enough to measure quantities related to only one of the two ratios. Since the data on temporal broadening are already available for a number of pulsars, extending the VLBI measurements of angular broadening (e.g. Gwinn et al. 1993) to a corresponding set of pulsars will be worthwhile. Such measurements, unlike the proper motion measurements, do not need long time-baselines or phase-referencing.

Our simple-minded analysis related to the Gum nebula region illustrates how even a less elaborate characterization of such extended scatterers using a few calibrators is useful in estimating the distance to pulsars with limited data on scattering. The present example also shows how such information can be used in the framework of the Taylor & Cordes model. The particular case of B0736–40 amply emphasizes the importance of reliable distances in the estimation of pulsar velocities, and we would like to stress that there could be many such cases, particularly amongst the high galactic latitude pulsars.

To conclude, the method presented here suggests an attractive possibility for distance estimation based on observables related to the interstellar scattering and scintillations. Such estimations would then play an important role in refining the present model for the distribution of electrons in our galaxy.

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REFERENCES

- Alcock C. R., Hatchett S. P., 1978, *ApJ*, 222, 456
- Bailes M., Manchester R. N., Kesteven M. J., Norris R. P., Reynolds J. E., 1990, *MNRAS*, 247, 322
- Blandford R., Narayan R., 1985, *MNRAS*, 213, 591
- Cordes J. M., 1986, *ApJ*, 311, 183
- Cordes J. M., Weisberg J. M., Boriakoff V., 1985, *ApJ*, 288, 221
- Desai K. M. et al., 1992, *ApJ*, 393, L75
- Frail D. A., Weisberg J. M., 1990, *AJ*, 100, 743
- Goodman J. M., Narayan R., 1985 *MNRAS*, 214, 519
- Gupta Y., Rickett B. J., Lyne A. G., 1994, *MNRAS*, 269, 1035
- Gwinn C. R., Bartel N., Cordes J. M., 1993, *ApJ*, 410, 673
- Lyne A. G., Manchester R. N., Taylor J. H., 1985, *MNRAS*, 213, 613
- Prentice A. J. R., ter Haar D., 1969, *MNRAS*, 146, 423
- Ramachandran R., Deshpande A. A., 1994, *JA&A*, 15, 69
- Ramachandran R., Mitra D., Deshpande A. A., McConnell D. M., Ables J. G., 1997, *MNRAS*, 290, 260
- Reynolds R. J., 1976, *ApJ*, 203, 151
- Rickett B. J., 1969, *Nat*, 221, 158
- Scheuer P. A. G., 1968, *Nat*, 218, 920
- Sivan J. P., 1974, *A&AS*, 16, 163
- Taylor J. H., & Cordes J. M., 1993, *ApJ*, 411, 674
- Vivekanand M., Narayan R., 1982, *JA&A*, 3, 399

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