NOTES ON DRIFT THEORY

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ABSTRACT

It is shown that there is a simpler way to derive the average guiding
centre drift of a distribution of particles than via the so-called
"single particle" analysis. Based on this derivation it is shown
that the entire drift formalism can be considerably simplified, and
that results for low order anisotropies are more generally valid than
is usually appreciated. This drift analysis leads to a natural al-
ternative derivation of the drift velocity along a neutral sheet.

Full derivations are given in Burger, Moraal and Webb (1985; re-
ferred to as BMW), of which copies will be available at the Conference.

1. Alternative Derivation of Drift Velocity. A particle at position x, with
momen entropy d3x around x. For a particle distribution function F(K, P, t) with den-
_xa w.r. t, time in the steady state (_ = 0), with employment of the Lorentz

where P_ are the Legendre polynomials.

The < p_ x > tensor is of the form:

\[
< p_\perp v_\perp > = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}, \quad < p_\parallel v_\parallel > = \frac{1}{3} < p v (1 - \frac{1}{5} F_{00} ) > \\
< p_\perp v_\parallel > = \frac{1}{3} < p_2 v_2 > = < p_3 v_3 > \\
< p_\perp v_\perp > = \frac{1}{3} < p (1 - \frac{1}{5} F_{00} ) > 
\]

\[
F(x, P, t) = F_{00} + F_{10} \cos \phi + F_{11} \sin \phi \cos \phi + F_{12} \sin \phi \sin \phi + F_{20} \cos \phi, 
\]

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For this form of $F$, the average drift velocity (1) becomes

$$\langle v_\Omega \rangle = \langle v_\mu \rangle + \frac{E \times B}{q} \pm \frac{1}{q}\left[ \frac{1}{q}\left( \frac{1}{p} \langle p \rangle_{\mu} \right) \cdot x x_b + \left( \frac{1}{q}\left( \frac{1}{p} + dp \right) \right) \cdot \left( \langle p \rangle_{\mu} \cdot x x_b - \frac{1}{q}\langle p \rangle_{\mu} \right) \right]$$

(6)

There are six noteworthy points about this seemingly familiar result: (1) It is the instantaneous average guiding centre velocity of particles in the volume element $d^3x$ in terms of the fields $E$ and $B$ inside $d^3x$. The usual "single particle" derivations (e.g. Rossi and OIbert, 1970) give a similar result, but for the time (gyroperiod) averaged drift velocity in terms of the fields $E_0$ and $B_0$ at the guiding centres. (ii) Our analysis does not need the usual "single particle" condition that $R < L$ (where $L$ is the smallest scale length of variation of $E$ and $B$). But, this does not mean that (6) is valid for any ratio $R/L$, as is discussed in Section 3. (iii) The result (6) is usually interpreted to hold only for gyrotrropic distributions, in which $F = F_1$, $F_2 = 0$ in (4) (e.g. Rossi and Olbert, 1970, Lee and Fisk, 1981). This too strict condition on $F$ stems from imprudent mixing of the $dp$ tensor with the pressure tensor $p = N(p < v^2 > - < p > < v >)$. (iv) If $F$ is of the simple form $F = (1 + \cos \theta)$, the underlined term in (6) exceeds the first one in $4 \pi$ only if $\gamma 2 \approx 3.56$. This represents a much higher anisotropy than usually found in Astrophysical applications, because then fully 95% of the particles have pitch angles in the forward range $0 \leq \theta \leq \pi/2$. (v) For first order anisotropies, $F_{Q}(\gamma 2) = 0$, the exact guiding centre velocity of particles in the volume $V$ is:

$$\langle v_\mu \rangle = \frac{E \times B}{q} \pm \frac{1}{q}\left[ \frac{1}{q}\left( \frac{1}{p} \langle p \rangle_{\mu} \right) \cdot x x_b + \left( \frac{1}{q}\left( \frac{1}{p} + dp \right) \right) \cdot \left( \langle p \rangle_{\mu} \cdot x x_b - \frac{1}{q}\langle p \rangle_{\mu} \right) \right]$$

(7a)

or

$$\langle v_\Omega \rangle = \langle v_\mu \rangle + \frac{E \times B}{q} \pm \frac{1}{q}\left[ \frac{1}{q}\left( \frac{1}{p} \langle p \rangle_{\mu} \right) \cdot x x_b + \left( \frac{1}{q}\left( \frac{1}{p} + dp \right) \right) \cdot \left( \langle p \rangle_{\mu} \cdot x x_b - \frac{1}{q}\langle p \rangle_{\mu} \right) \right]$$

(7b)

where $p = (N/3)<p v>$ is the scalar pressure. Because of the error mentioned in (iii), this is usually quoted as an approximate result, strictly valid for isotropic distributions only. (vi) Since

$$\langle v \times b \rangle = \frac{1}{B} \left[ \frac{B x V b}{B^2} + \frac{\langle v \times B \rangle}{B} \right]$$

(8)

the last term in (7) is the sum of the usual gradient and curvature drift.

2. Average Particle Velocity $\langle v \rangle$ and Nomenclature. From the first moment of the Vlasov Equation $\partial F / \partial t + \langle x v \rangle F + B \times \langle v F \rangle = 0$, it is readily shown that in the steady state the average particle velocity for a distribution of the form (4) is:

$$\langle v \rangle = \langle v_\mu \rangle + \frac{E \times B}{q} \pm \frac{1}{q}\left[ \frac{1}{q}\left( \frac{1}{p} \langle p \rangle_{\mu} \right) \cdot x x_b + \left( \frac{1}{q}\left( \frac{1}{p} + dp \right) \right) \cdot \left( \langle p \rangle_{\mu} \cdot x x_b - \frac{1}{q}\langle p \rangle_{\mu} \right) \right]$$

(9)

The underlined term is identical to the one in (6). For first order anisotropies this reduces to the well-known form

$$\langle v \rangle = \langle v_\mu \rangle + \frac{E \times B}{q} \pm \frac{1}{q}(p N) B \times V b,$$  

(10a)

or in the differential case

$$\langle v_\Omega \rangle = \langle v_\mu \rangle + C B \times V b + pv/(3qU) B \times V b$$

(10b)

where $U = p^2(1/4) / F d^3$ is the differential number density in $(p, p + dp)$, and $C = 1 - (1/3U) / \langle p \rangle (p U)$ the Compton-Getting factor. The results (10) are standard in cosmic ray literature.

From the definition $x_g = x - R$ it follows that $\langle x_g \rangle = \langle x \rangle - \langle dR / dt \rangle$. The average circulation velocity $\langle dR / dt \rangle$ is usually called the diamagnetic drift, and together with $\langle v \rangle$, these two velocities are frequently referred to as collective plasma drifts. This is in opposition to the guiding centre drift which is called a "single particle drift". The average guiding centre drift seems equally collective to us. We also argue that the guiding centre drift is the only drift, because it is designed to tell you where the distribution goes after the trouble is some, typically dominant circular motion of each particle has been subtracted.

In BMW these arguments are extended to the non-steady state ($a / at = 0$). After multiplication of all velocities with $qN$ it is easily shown that for first order anisotropies...
\[ j = \frac{1}{\rho} j_g + j_b + j_p = \frac{1}{\rho} j_g + \nabla \times M + \frac{\partial \Pi}{\partial t}, \]  

(11)

where \( \Pi = -\nabla \phi \cdot \vec{v} > 0 \) is the diamagnetic moment per unit volume and \( \Pi = \vec{B} \times \langle \vec{p} \rangle \) the polarisation vector of the plasma. The total plasma current density is therefore the sum of the guiding centre (or free) current density, the diamagnetic current density and the polarisation current density. When standard "single particle" drift analyses are used, the equivalent result for (11) can only be written down readily for the perpendicular components (e.g. Parker, 1957). Northrop (1961, 1963) also included the parallel components but he needed the introduction of a distribution function \( F_0 \) for guiding centres in addition to \( F \), and elaborate algebra to do it. By contrast our result is essentially true per definition.

3. Neutral Sheet Drift. Standard drift theory breaks down at neutral sheets (\( B=0 \)) because the condition \( R/L \ll 1 \) is violated. Our derivations are independent of this ratio but they still break down. The reason follows from Figure 1 which shows a field \( \vec{B} = \vec{B}(x) \hat{\epsilon}_x \), with \( \vec{B}(x) \) homogeneous in \( x \), and \( \partial \vec{B}/\partial x \) any arbitrary large positive value. The drift of particles such as (a) and (b) is perfectly well described by the last term of (7), independent of the magnitude of \( \partial \vec{B}/\partial x \). However (8) shows that at \( x=0 \), \( \nabla \times \vec{B} = 0 \), while Figure 1 suggests that individuals drift with finite velocity. Consequently \( \langle \vec{v}_d \rangle \) cannot be infinite (as it was used by Jokipii and Thomas (1981, and references therein)). The obvious reason for this breakdown is that the drift velocity at \( x=0 \) depends on the point angle at the point of crossing.

The drift in and around a neutral sheet is readily calculated if \( \vec{B} \) is given by \( \vec{B}(x) = -2H(x) \vec{e}_x \), where \( B_0 \) is a constant and \( H \) the unit step function at \( x=0 \). Figure 2 shows the Orbit of a particle with velocity \( v=(v,0,0) \), projected onto the plane \( \theta=\pi/2 \). It just crossed the sheet at point \( x \) under phase angle \( \phi \), and will again do so at point \( b \) after having completed a projected arc length \( s=2R_0(\pi-\phi)\sin \theta \), where \( R_0=\rho/(qB_0) \). At that time the guiding centre abruptly jumps a distance \( \ell=2R_0\sin \theta \sin \phi \) in the direction \( -\vec{e}_y \). Therefore the component of the (time averaged) guiding centre velocity in the direction \( -\vec{e}_y \) may be taken as

\[ v_{gy} = \ell/\Delta t = (\ell/s) v \sin \theta = \left[ \frac{v}{(\pi-\phi)} \right] \sin \theta \sin \phi \]  

(12)

From the relation \( \cos \phi = \cos \theta (x/R_0 \sin \theta) \) it follows that of all the particles momentarily inside \( d^3x \), at a distance \( x \) from the sheet, only those with

\[ \phi_1 < \phi < \phi_2, \quad \text{where} \quad \sin \phi_1 = x/(2R_0) \quad \text{and} \quad \cos \phi_1 = 1-x/(2R_0 \sin \theta) \]

(13)

can cross the sheet before completing a full orbit. Therefore the directionally averaged drift velocity over an isotropic particle distribution inside \( d^3x \) is

\[ \langle v_g \rangle = -e_y (v/4\pi) \int_0^{\pi} \int_0^{\pi} \sin \phi_2 \sin \phi_1 \left[ \frac{\partial \Pi}{\partial \phi} \right] \]  

(14)

The \( x \)-component of the drift velocity oscillates and does not contribute to the average, while the \( z \)-component of the average is zero for an isotropic distribution. The integral (14) can be evaluated as a series at \( x=0 \) to give \( \langle v_g \rangle = -0.463 e_y \) while its numerically calculated value in the range \(-2R_0 \leq x \leq 2R_0 \) is shown in Figure 2.

This interpretation of guiding centre drift at a neutral sheet differs considerably from previous ones. Firstly, there is no sheet current density of the form \( \vec{j}(x)=\rho_0(x) \vec{e}_y \) as is sometimes suggested. In fact the assumed isotropy implies \( \langle j \rangle = 0 \) everywhere, even in a volume element \( d^3x \) at \( x=0 \). Secondly, the distribution in the entire range \(-2R_0 \leq x \leq 2R_0 \) progresses (drifts) in the direction \(-\vec{e}_y \), instead of the infinite sheet drift current \( \vec{j}_g=\rho_0(x) \vec{e}_y \) derived by Jokipii et al. (1977) from the \( \nabla \times \vec{B}/B^2 \) term in \( \vec{F} \).

As an example we consider the motion of cosmic rays in the interplanetary magnetic field.
\[ B = B_0 (r_0 / r)^2 \left[ e_{r'} - (\Omega r \sin \theta / V) e_{\theta'} \right] \left[ 1 - 2H(\theta - \pi / 2) \right], \]  
(15)

where \( \Omega \) is the angular velocity of the Sun, \( V \) is the radial solar wind velocity and the function \( 1-2H \) models a flat neutral plane at \( \theta = \pi / 2 \). The neutral sheet drift (14) will be experienced by cosmic ray particles within an angle \( \Delta \Omega = 2R_0 / r \) from the plane. If \( V = 400 \) km s\(^{-1} \), \( \Omega = \left(2\pi / 27\right) \) day\(^{-1} \), \( r = 1 \) A.U., and \( B_0 = 5/12 \) nT (\( | B | = 5 \) nT at Earth), it is readily shown that

\[ \Delta \Omega \approx 0.72 (P/P_0) r (r^2 + r_0^2)^{-1/2} \text{ degrees}, \]  
(16)

where \( P \) is particle rigidity with \( P_0 = 1 \) GV. Typical cosmic ray protons with kinetic energy \( T = 250 \) MeV, \( P = 0.75 \) GV are therefore convected along the neutral plane in a region with thickness \( 2\Delta \Omega = 1 \) degree. This neutral plane drift effect is not included in existing drift models of cosmic ray modulation. Jokipii and Thomas (1981, and references therein) used the \( \delta \)-function type drift velocity at the neutral plane, derived from the \( V \times B / B^2 \) term. Potgieter and Moraal (1985) used a finite neutral plane drift velocity pattern, similar to that of Figure 2, but not based on the fundamental arguments used here. In their model the angular region \( \Delta \Omega \) in (16) could i.a. be varied in an empirical and unjustified way, and it is significant that cosmic ray observations were better explained with finite neutral plane drift in a region \( \Delta \Omega \geq 1^\circ \), than with a \( \delta \)-function type drift at \( \theta = \pi / 2 \) only.

References
Northrop, T.G.: 1963, Adiabatic Motion of Charged Particles, Interscience, N.Y.