Quasi-Local and Non-Local Intensity Gradients of Anomalous Cosmic Rays

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Abstract

The standard method to calculate spatial intensity gradients of energetic particles in the heliosphere is the "non-local" gradient (NLG) method [3], which requires observations from at least three spacecraft to simultaneously determine radial (g_r) and latitudinal (g_λ) gradients. We present a novel technique to calculate "quasi-local" gradients (QLG) [1] and apply the method to anomalous cosmic ray (ACR) ions during the 1994–1999 recovery phase. Under the prevailing conditions, the QLG method requires fewer than three spacecraft to determine g_r and g_λ. We briefly compare some assumptions, strengths, and weaknesses of the QLG and NLG methods. We use QLG with Voyager 1 & 2 (V1 & V2) Low Energy Charged Particle (LECP) measurements [2] to determine ACR gradients, which agree well with both a phenomenological ACR intensity model and a numerical, time-dependent solution to the Fokker-Planck equation [1]. A principle result is the unexpected determination of $g_\lambda < 0$ for ACRs having rigidities less than ~ 2 GV during the positive heliomagnetic polarity.

1. Quasi-Local Gradient Method

Under steady state conditions, the QLG method can be employed to simultaneously determine g_r and g_λ from two spacecraft. The required conditions for relative motion between the two spacecraft are mild, e.g., both spacecraft cannot be stationary nor following the same linear trajectory in the heliolatitude (λ) vs. helioradius (r) plane. We start with the same differential expression for the intensity j in terms of constant g_r and g_λ that many others authors have used to determine gradients traditionally [3]: $\frac{dj}{j} = g_r dr + g_\lambda d\lambda$. Solving for $ln(j)$ and dividing by Δr we arrive at the following:

$$\frac{ln(j_1/j_2)}{\Delta r} = g_r + \frac{\Delta\lambda}{\Delta r} g_\lambda, \tag{1}$$

where Arabic indices identify each spacecraft and $\Delta r \equiv r_1 - r_2$ and $\Delta\lambda \equiv \lambda_1 - \lambda_2$ are defined. We define $x \equiv \frac{\Delta\lambda}{\Delta r}$ and $y \equiv \frac{ln(j_1/j_2)}{\Delta r}$ for convenience, yielding $y = g_r + x g_\lambda$. We have learned that Eq. 1 was independently used by Paizis et al. [4], but their subsequent procedure is unlike the QLG method.

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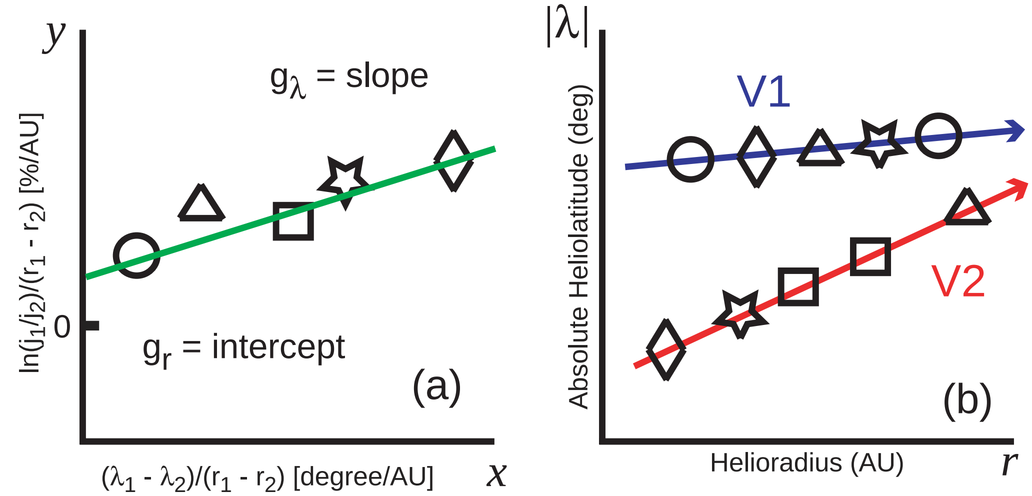

Fig. 1. Schematic (a) QLG plot and (b) $|\lambda|$ vs. r trajectories for V1 and V2. Five sample "event pairs" are illustrated, one for each symbol. Each pair of events from panel (b) is used to calculate a single (x, y) data point in the QLG plot (a). The fit (a) to the set of all (x, y) points is used to calculate the radial and latitudinal gradients from the intercept and slope of the line, according to Eq. 1. When the procedure is actually carried out *all possible* event pairs are used (cf. Figure 2), unlike this example.

The QLG method proceeds by calculating x and y for *all possible pairs* of separate event measurements $j(r, \lambda, t)$. These pairs include events at different times along the same spacecraft trajectories—"self-pairs"—as well as pairs that use both spacecraft (see Figure 1b for a schematic example). Once all pairs are calculated, the (x, y) data are plotted and fitted with a line (Figure 1a). The slope and intercept of this fit determine g_λ and g_r. Note that only selected pairs—*not* all possible pairs—are illustrated in Figure 1, to prevent clutter, but for the data displayed in Figure 2 the result of all possible event pairs is shown. The self-pair data is what suggested the use of "quasi-local" in naming the QLG method, since the locality of the measurement is only restricted by the cadence of the averaging interval, unlike the NLG method which obtains a gradient "between" a given set of spacecraft.

2. Validity of the QLG and NLG Methods

Both the QLG and the NLG methods rely on certain, analogous, assumptions that do not hold in all cases. The QLG method has lower temporal resolution, but higher spatial resolution (limited by the data cadence), while NLG has lower spatial and higher temporal (limited by the data cadence) resolution. QLG relies on an assumption about the temporal variations (e.g., steady state) over

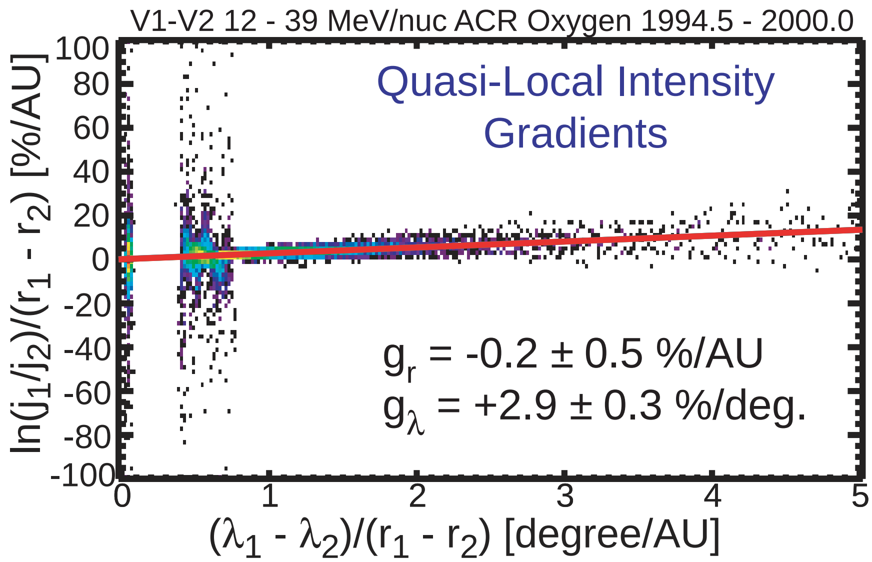

Fig. 2. Over 11,000 event pairs are plotted using a color scale in this QLG plot for V1 & V2 12–39 MeV/nuc ACR O, based on 26-day averaged intensity measurements [2]. The linear fit to these data points yields the intensity gradients shown, where Eq. 1 was used. This analysis must be carried out for each species and energy range desired (see Figure 3 for a summary of these results).

sizable periods of time, while NLG requires symmetry and simplicity of the spatial variations over large distances. For high-energy ACRs the spatial gradients are very small as are the time variations, so both methods are likely to be in general agreement, as we observe [1]. For Galactic cosmic rays the spatial gradients are small, but temporal variations may last longer into the recovery period, so the NLG method is likely to be superior to QLG. For low energy ACRs, large spatial gradients are expected, but there is significant evidence that steady state conditions prevail [1], so the QLG would be expected to be valid. The NLG method might fail in this scenario, since the large spatial variations over vast regions of the heliosphere are poorly known. For example, since a third spacecraft is required, use of the NLG method must employ measurements from Pioneer 10 (P10), which is on the opposite side of the Sun than V1 and V2. Any use of P10 is conjunction with V1 and V2 requires a significant assumption about the global morphology of the heliosphere. This assumption is minimized in the QLG calculations since V1 and V2 are both closer to the apex direction of the heliosphere. This is an example of a circumstance where we argue it is preferable to use the QLG method rather than the NLG method. Of course, were three or more spacecraft in close proximity to one another, one would prefer the NLG to the QLG method, but this is not the case in the outer heliosphere.

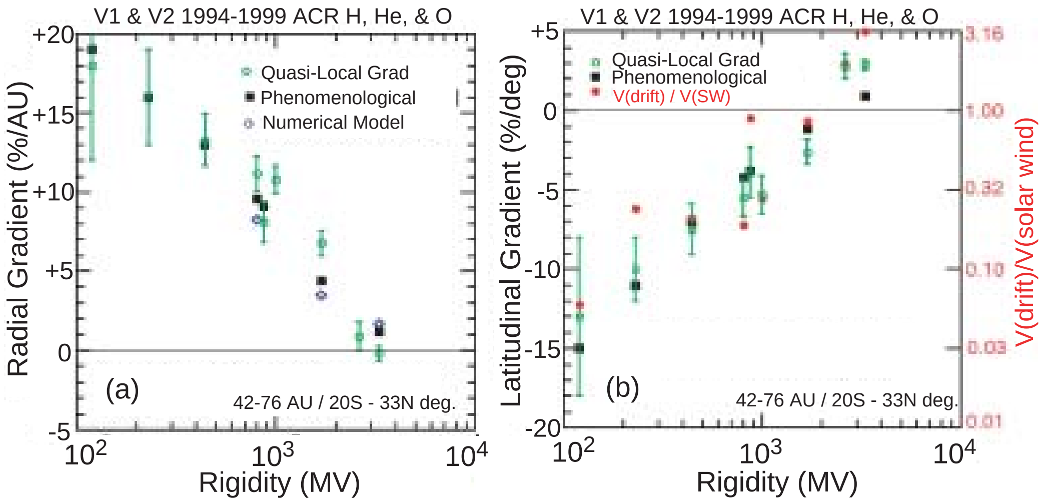

Fig. 3. V1 & V2 ACR H, He, & O (a) radial and (b) latitudinal gradients, 1994–1999.

3. Radial and Latitudinal Gradients

In Figure 3 we display the g_λ and g_r values for ACRs calculated using the QLG technique with V1 & V2 H, He, and O measurements. They are plotted as a function of rigidity, along with results from a numerical, time-dependent transport model and a simultaneous phenomenological fit to all of the LECP ACR data [1]. In Figure 3a, the general agreement between these three methods can be seen. In Figure 3b the spherically symmetric transport model makes no direct prediction regarding latitude, so only the two remaining methods are shown, also in general agreement. In addition to this, the ratio of the nominal drift velocity to solar wind velocity is shown, suggesting that the negative latitudinal gradients occur for the lowest rigidity ACRs, where drifts are less important. A possible mechanism causing the $g_\lambda < 0$ result is the latitudinal dependence of the solar wind speed, with the high latitude, high speed wind tending to impede the entrance of ACRs into the heliosphere relative to low latitudes.

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