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Comment on “Spectral features of SKR observed by Cassini/RPWS: Frequency bandwidth, flux density and polarization” by Patrick Galopeau et al.

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1. Introduction

[1] Galopeau et al. [2007] (hereinafter referred to as G07) recently presented a study of Saturn Kilometric Radiation (SKR) spectral features observed by Cassini/Radio and Plasma Wave Science, High-Frequency Receiver (RPWS/HFR), in which they obtained the following results:

[2] 1. They propose a classification of the SKR spectrum in three components: component A spans from 3.5 kHz, the lowest-frequency channel of the receiver, to 70–80 kHz; component B is observed from 70–80 kHz to 800–900 kHz; component C lies within the 800–900 kHz to 1200 kHz interval. The physical origin of these components is questioned without answering for components A and C; component B is the well-known auroral SKR [see, e.g., Zarka, 1998]. Galopeau et al. [2007] describe the SKR spectrum morphology especially of B and C components in reference to the morphological classification of Genova et al. [1983], and conclude that the SKR spectrum is variable and unpredictable at time scales of hours to days.

[3] 2. They find a weak linear polarization ($\leq 10\%$) in components A and C, which appear thus to be elliptically polarized, without deciding if it is real or due to inaccurate modeling and/or calibration of the HFR polarization response.

[4] 3. They compare their results to the SKR spectrum model of Galopeau et al. [1989].

[5] We comment below on each of these results.

2. SKR Spectrum Classification and Subcomponents

[6] As can be seen in Figures 2, 3, 4, 6, and 7 of G07, component A is characterized by a spectral slope between f^{-1} and f^{-2} . Our Figure 1a displays the dynamic spectrum of the data recorded on day 2005-357 (23 December 2005), when this variable low-frequency noise and the SKR are well visible. Component A is detected when Cassini is in Saturn’s magnetosphere on day 2005-357, from local time

(LT) ~ 1000 and distance $\sim 15 R_S$ (Saturn radii) as well as when it is in the solar wind on 2006-008 (8 January 2006), from ~ 0600 LT and distance $\sim 46 R_S$. As shown on our Figure 2, a similar low-frequency noise was also detected when Cassini was several AU from Saturn, as well as very near perikrone. Its spectrum and intensity thus do not depend on location or distance relative to Saturn. Consequently this component cannot be attributed to a Saturnian radio source. The most plausible origin for this noise is plasma impact noise on the spacecraft and antennas in f^{-2} , as described by Meyer-Vernet [1985] and Meyer-Vernet and Perche [1989], and possibly also f^{-1} noise. The level of the plasma impact noise spectrum depends on the plasma temperature, the presence of beams; thus the thin and thick morphology of component A described by G07 simply reflects the variability of the local plasma conditions.

[7] The absent or disconnected A component, for example on day 2006-009 (9 January 2006), is likely to arise from the way the background is computed and subtracted from the data displayed. HFR background determination has been documented in detail by Zarka et al. [2004]. The specific processing applied by G07 is not explained, but we note that minimum spectra (red lines of Figures 2–7 and 9 of G07) often display variations similar to median/average spectra, and that all levels (minimum to maximum) display peaks and gaps related to interference lines; the HFR is polluted by interference lines from the Cassini power converters at all harmonics of 100 kHz.

[8] Low-frequency emissions are actually observed around Saturn [Gurnett et al., 1981] and have been named “n-SMR emission” [Louarn et al., 2007] for emissions in the 3 kHz to 10 kHz range, and “n-SKR emissions” [Lamy et al., 2008b] in the 10 kHz to 40 kHz range. These two low-frequency narrow-band emissions have different flux and polarization characteristics. These emissions were not present in the data presented by G07.

[9] The components B and C discussed by G07 only differ by their frequency range and linear polarization: component C shows a small nonzero linear polarization; component C is at higher frequency than component B. According to G07, component C is described as a high-frequency component of the SKR, as supported by their Figure 7 showing a spectrum with a power drop around 800 kHz. We note that G07 mention a range from 800–

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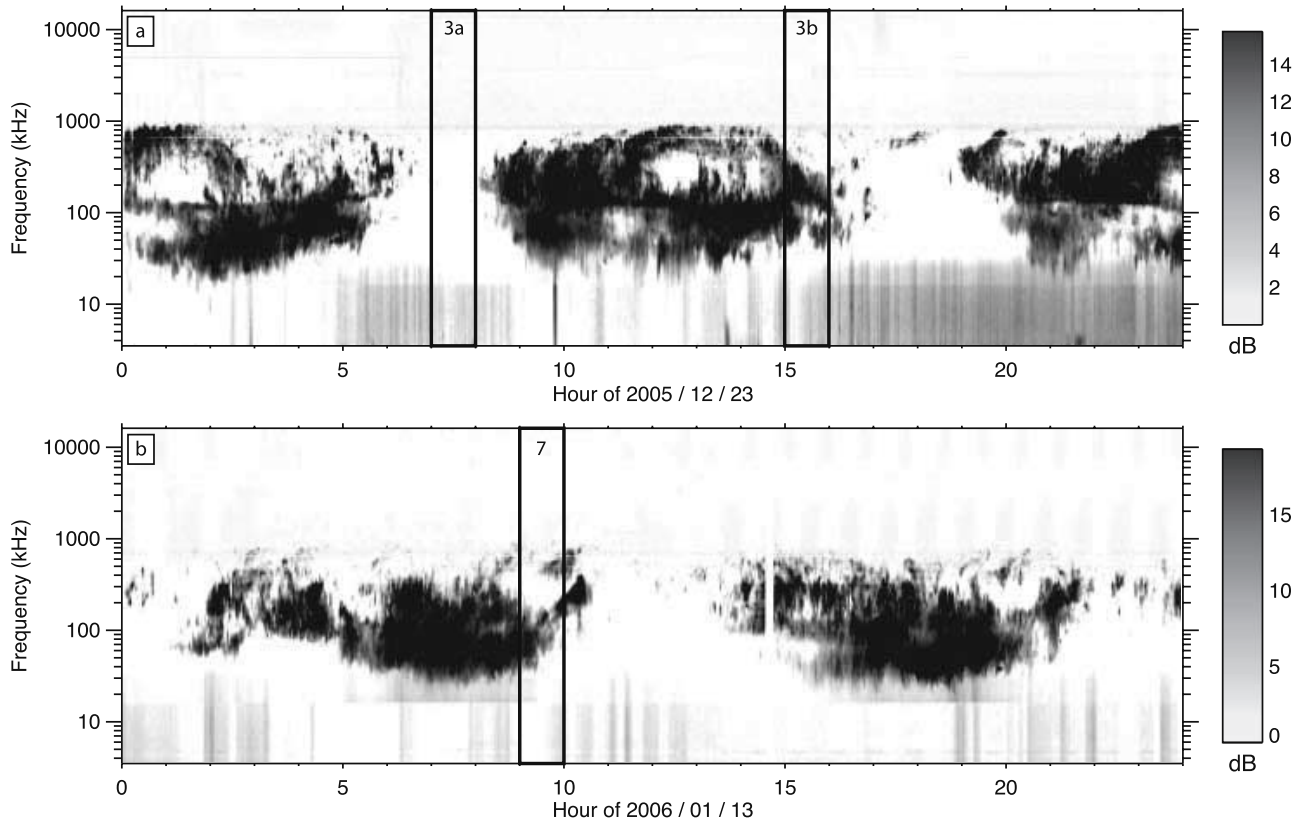


Figure 1. Dynamic spectrum of the power received on the dipole antenna (E_x) during (a) day 2005-357 and (b) day 2006-013. The grey scale is in dB above the background. This background has been computed for each frequency channel over the whole day and has been subtracted from the dynamic spectrum. The black rectangles labeled 3a, 3b, and 7 show the data used to compute Figures 3a (top), 3b (bottom), and 7 of *Galopeau et al.* [2007], respectively.

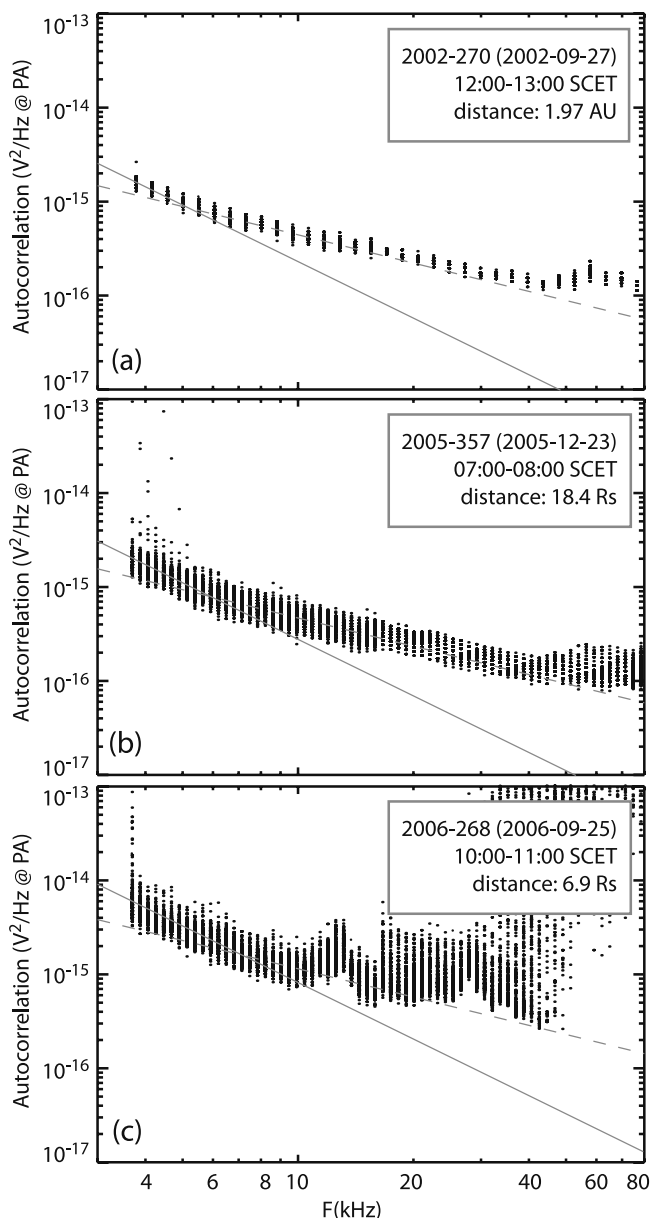


Figure 2. Low-frequency HFR spectrum (in V^2/Hz at the receiver inputs) measured on the E_x dipole: (a) in the solar wind far from Saturn, (b) on 2005-357, and (c) at a perikrone. The plain and dashed lines show f^{-2} and f^{-1} slopes, respectively. Data time intervals are given in spacecraft event time (SCET).

900 kHz to 1200 kHz although almost no emission appears above 1 MHz in their displayed images. However, the dynamic spectrum of that interval (shown in our Figure 1b) reveals ubiquitous arc-shape structures in this frequency range. A spectrum restricted to the interval 0900 to 1000 spacecraft event time (SCET) of 2006-013 gives the impression of an isolated burst. Such a structure is more likely to be due to visibility effects applied to complex auroral source structure, as discussed by *Lamy et al.* [2008a]. Depending on how the background is computed, the power converter interference lines can also induce peaks

or gaps in the resulting SKR spectra, as clearly visible in Figures 3, 4, 6 and 7 of G07. Their Figure 7 shows additional spectral power drops at 300 and 500 kHz. Below we also show that the slightly different polarization of component C is likely to have a spurious origin. Distinct sources or processes for components B and C could be supported by measurements of different goniopolarimetric properties (e.g., opposite polarization for the same hemisphere of origin, that would indicate different emission modes), but no such measurements are performed by G07. However, Cassini is too far from Saturn ($>30 R_S$) to be able to obtain accurate goniopolarimetric discrimination based on the direction of arrival.

[10] Although no detail is provided on the goniopolarimetric techniques used by G07, the operating mode of the instrument (the so-called dipole mode, i.e., providing only four independent measurements for each data sample) allows us to obtain four wave parameters only, out of six [see *Cecconi and Zarka, 2005*]. In order to obtain the full polarization degree of the incoming wave, the authors of G07 had to assume a source position and solve for the four Stokes parameters [*Kraus, 1966*]. The source position is usually set to the center of Saturn in such a case. Although it is possible to refine the assumed position of the source in altitude and latitude, with an emission model [see, e.g., *Galopeau et al., 1989*], there will still be an indetermination on the longitudinal location of the source. Hence, two sources emitting at the same frequency from a different longitude will induce different measurements. Using a goniopolarimetric inversion with an assumed location for the source will thus apparently produce different polarization results. *Lamy et al.* [2008a] showed that during the period of time studied by G07, the observed SKR arcs are very well reproduced by a simple model with subcorotating sources. They also showed that the high-frequency part of the spectrum (above ~ 800 kHz) is composed of emissions from the northern hemisphere, whereas the lower-frequency emissions come from the southern one. The angular distance between northern and southern sources is $\sim 3^\circ$, as seen from Cassini for the period studied in their Figure 7 (day 2006-013 (13 January 2006), 0900-1000 SCET). Such an angular separation between sources is not negligible and will generate apparent polarization discrepancies if the assumed source position is the same for both emissions. It is possible to estimate the error on the degree of linear polarization using the same error-simulation routines as *Cecconi and Zarka* [2005]. The input parameters of the simulation are the following: an actual Cassini/Saturn geometrical configuration at day 2006-013, 0900-1000 SCET; a fully circularly polarized wave; an assumed source position in the southern hemisphere ($2R_S$ southward from Saturn's center); and actual source position in the northern hemisphere ($2R_S$ northward from Saturn's center). This simulation gives an apparent degree of linear polarization of 0.08, comparable to that observed by G07.

[11] About spectrum variability, we simply note that only 5 days of data are analyzed by G07 (days 2005-356, 2005-357, 2006-008, 2006-009, and 2006-013). No criterion is given for the selection of such a limited subset among the >4 years of quasi-continuous available RPWS/HFR data. A discussion of spectral shape alone (as opposed to dynamic spectrum modeling [*Lamy et al., 2008a*]) is not relevant,

unless significant statistical results are obtained. The study of G07 relies upon a too limited data interval. Its conclusions on spectral shape have no generality; hence its conclusion limited to a “variable and unpredictable envelope.” A statistical study of the SKR has since been published [Lamy *et al.*, 2008b] that provides new insights on the dependence of the SKR spectrum with respect to the latitude and local time of observation. No evidence for a high-frequency elliptically polarized emission was reported by [Lamy *et al.*, 2008b].

3. SKR Elliptical Polarization

[12] Galopeau *et al.* [2007] presented possible detection of elliptical polarization in components A and C. They questioned the former results on SKR polarization degree by Cecconi *et al.* [2006], arguing that a very small fraction of the data (<1%) were selected for that study. It was explained by Cecconi *et al.* [2006] that a severe selection must be applied to the data in order to obtain accurate polarization results. Since that paper, the processing chain of the Cassini/RPWS/HFR data has been improved, allowing better treatment of the low-intensity signals. Hence, the signal-to-noise ratio (SNR) low limit has been lowered from ~ 23 dB [Cecconi and Zarka, 2005] to ~ 15 dB. The following selection criteria must then be applied in order to obtain accurate results: $\text{SNR} \geq 15$ dB and angular distance between the antenna’s plane and the wave direction of arrival ($\beta_{XZ} \geq 20^\circ$ in absolute value. With these criteria, one can retrieve wave polarization with an accuracy ~ 0.1 on the polarization degrees, direction of arrival within $\sim 1^\circ$, and flux density within ~ 1 dB. It is also necessary to remove the frequency channels polluted by the power converter interferences, which is approximately 1 out of 4 above 325 kHz, for the operating mode used on day 2006-009.

[13] Our Figure 3 shows the distribution of all polarization degrees with different data selections for day 2006-009 (see caption of Figure 3). We removed the frequency channels polluted by the power converter interferences lines. Figure 3 clearly shows that the data selection on both SNR and β_{XZ} rejects data samples with spurious linear polarization. It is also clear that a large fraction of the data is circularly but partially polarized (see Figure 3, right column). With the final data selection, we get:

$$\begin{aligned} Q &= 0.007 \pm 0.078, \\ U &= 0.006 \pm 0.076, \end{aligned} \quad (1)$$

which indicates a linear polarization degree statistically consistent with zero, and thus there is no evidence of elliptical polarization contrary to what is reported by G07.

[14] We also note that G07 chose to study data recorded when Cassini was in Saturn’s equatorial plane (latitude $< 1^\circ$). In this case, emissions from both hemispheres are observed simultaneously by the HFR. Even if pure left-hand (LH) and right-hand (RH) circular emissions are produced (thus with $|V| = 1$, $U = 0$ and $Q = 0$), their superposition can result in any degree of circular polarization. This is clear on the right column of Figure 3. We also note that G07 chose to display and discuss only LH spectra in their Figures 2–6, while their Figure 9 demonstrates that

RH polarization is actually more intense during the intervals that they studied.

[15] Finally, elliptically polarized SKR has been recently detected during high-latitude orbits (above $\sim 30^\circ$) from autumn 2006 until spring 2007, over the whole SKR band, and at high SNR (G. Fischer *et al.*, Elliptical polarization of Saturn kilometric radiation observed from high latitudes, submitted to *Journal of Geophysical Research*, 2009). The latitudinal range of observation for elliptically polarized SKR is not compatible with G07 results, which were obtained during equatorial orbits only.

4. Comparison to Theoretical Spectrum

[16] Galopeau *et al.* [2007] claim to compare their results to the SKR spectrum model of Galopeau *et al.* [1989]. However, the suggestion that component C may originate from high latitudes only comes from the comparison of its frequency range to the distribution of electron cyclotron frequencies near Saturn. Maximum spectra, displayed in $V^2 m^{-2} Hz^{-1}$ at $50 R_S$, are not compared quantitatively with the theoretical predictions displayed in their Figure 10 in $W m^{-2} Hz^{-1}$ at 1 AU. The scale difference is $\sim 10^{-6}$. It would be important to comment on the fact that highest flux densities of G07, well in excess of $10^{-12} V^2 m^{-2} Hz^{-1}$ at $50 R_S$, are thus well above the maximum theoretical spectrum of Figure 10 of G07.

[17] Highest-frequency SKR (e.g., “component C”) is also detected at frequencies above the upper limit of the theoretical spectrum of their Figure 10. This limit was computed by Galopeau *et al.* [1989] under the assumption of a dipolar magnetic field and of a maximum ratio $(f_p/f_c)^2$ of 0.148 for CMI operation. The latter is an upper limit derived from the inhomogeneous CMI theory [Le Quéau *et al.*, 1985], but it was demonstrated in further works [Galopeau and Zarka, 1992; Hilgers, 1992; Zarka *et al.*, 2001] that an actual operating limit is rather between 0.01 and 0.02. A proper test of the theory should thus involve the use of that operating limit together with a realistic Saturnian field model (Z3 [Connerney *et al.*, 1984], SPV [Davis and Smith, 1990], or even the inclusion of a magnetic anomaly [Galopeau and Zarka, 1992]).

5. Conclusions

[18] From the above discussion, we have seen the following: (1) Component A is not a radio component of Saturnian origin, but consists of plasma impact noise plus possible f^{-1} noise. The discussion of SKR spectral morphology is not relevant without a discussion of spectrotemporal shape (such as radio arcs modeling). Visibility effects related to the observer’s position in the anisotropic source beam should be taken into account. No convincing evidence is presented in favor of different origins for components B and C. Components B and C are likely to be the well-known SKR spectrum extending from a few 10s of kHz to >1 MHz. No significant statistical result is obtained on spectral shape and variability. (2) The linear polarization detected in components A and C is likely to be spurious. (3) Quantitative comparison to theory remains to be done.

[19] As a concluding remark, we insist upon the fact that careful data selection, calibration, and knowledge of error

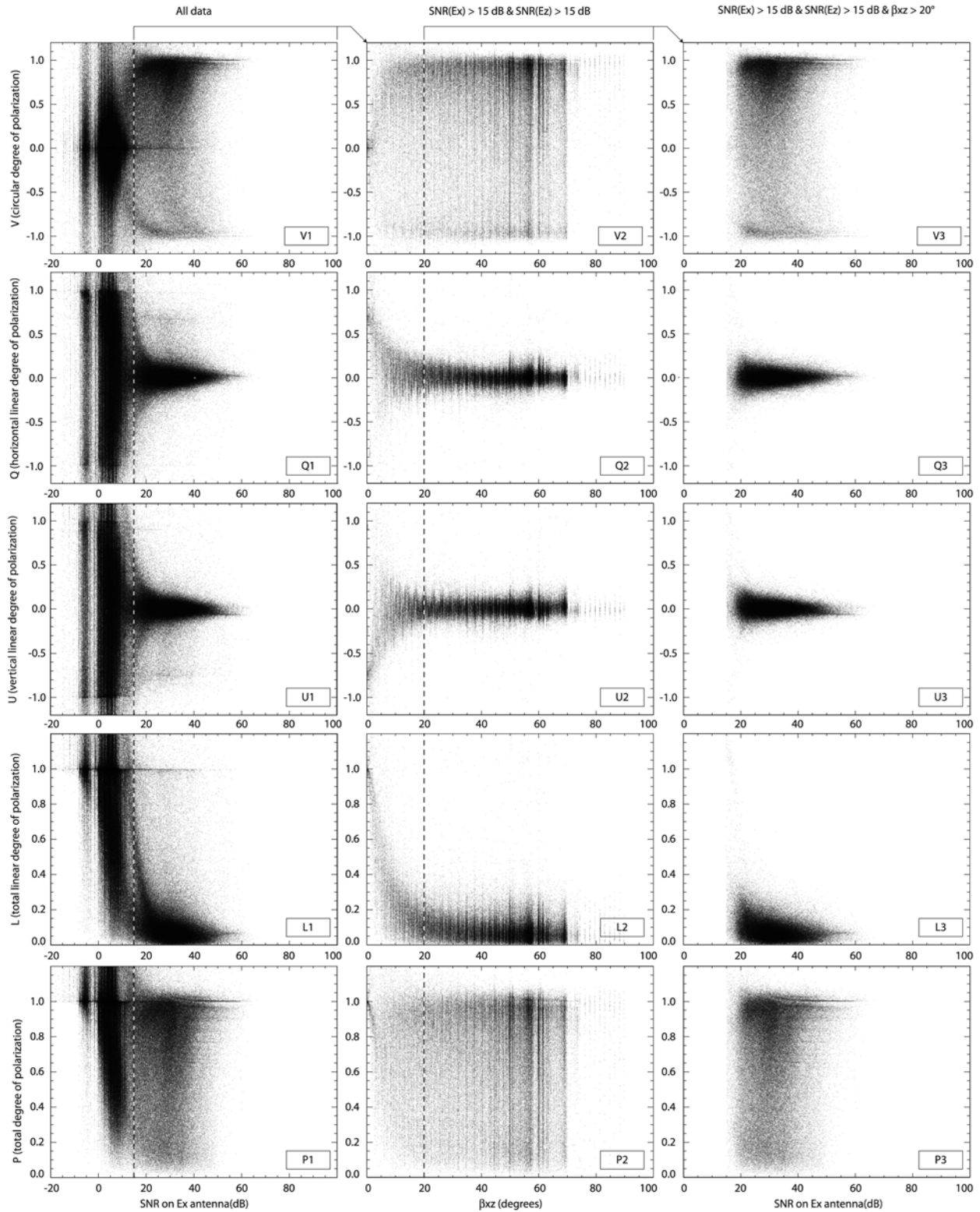


Figure 3. Polarization degree distributions for day 2006-009. From top to bottom: circular polarization degree (V); vertical linear polarization degree (Q); horizontal linear polarization degree (U); total linear polarization degree ($L = \sqrt{U^2 + Q^2}$); and total polarization degree ($P = \sqrt{L^2 + V^2}$). From left to right: all data versus SNR on the E_x dipole; data points with SNR > 15 dB on each channel versus β_{XZ} angle; and data points with SNR > 15 dB on each channel and $\beta_{XZ} > 20^\circ$ versus SNR on the E_x dipole. The vertical dashed lines are the minimum selection thresholds to be applied to the data [Cecconi and Zarka, 2005]. Below these thresholds, background noise biases the results.

sources is absolutely required when analyzing radio goniopolarimetric data. The interpretation of G07 requires taking into account possible visibility effects. Without that, erroneous conclusions may easily be drawn from the data.

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