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MEMORANDUM **SEPTEMBER 1, 1991**

TO: Dr. Donald K. West/GSFC

FROM: Dr. J. Hunter Waite, Jr./SwRI JHW

SUBJECT: Final Report for NASA Grant NAG5-1429
SwRI Project No. 15-3123-028

The primary purpose of this grant was to support simultaneous IUE and ROSAT observations of the Jovian aurora. Two sets of observations were obtained. One set during the ROSAT all sky survey in October of 1990 and the pointed ROSAT observations of GO Bagenal in April of 1991. In addition to supporting the observations, theoretical calculations of the expected brightness of H_2 ultraviolet and electron bremsstrahlung were also partially supported by this work. A preprint of a related paper in press in the Journal of Geophysical Research which reports this work is presented as an Appendix.

Comment on "Bremsstrahlung X Rays from Jovian Auroral Electrons"
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The subject of this Comment is a recent paper by D.D. Barbosa in which it is argued that electron bremsstrahlung is the most likely source of the auroral x-ray emissions that have been observed at Jupiter [Barbosa, 1990]. Barbosa bases his argument on observational and theoretical studies of the production of secondary electrons in the Earth's aurora. As this Comment will show, however, Barbosa's interpretation is flawed because it ignores the constraint that the primary electron distribution parameters place on the parameters for the secondary electron distribution. As a result, Barbosa's postulated secondary electron fluxes are over three orders of magnitude greater than the theory of auroral electrons permits.

BACKGROUND

The identity of the particles involved in Jovian auroral activity has not been conclusively established and remains a subject of some controversy. Data relevant to this question comprise both observations of auroral emissions obtained by remote sensing at x-ray, UV, IR, and radio wavelengths and *in situ* particle measurements made by the energetic particle detectors on Voyager. These data do not permit the identification of any one single source for the Jovian auroral emissions. The UV data tend to point to precipitating electrons (in the energy range of 10-50 keV) as the dominant source, while the *in situ* measurements reported by Gehrels and Stone [1983] suggest that the precipitation of energetic heavy ions (oxygen and sulfur ions in the energy range of 40-1000 keV) plays an important role in auroral processes. X-ray observations have also been interpreted as evidence for heavy ion precipitation [Metzger et al., 1983]. Waite et al. [1988] have attempted to reconcile these interpretations by proposing that *both* electrons and ions, depositing their energy at different altitudes and latitudes, play a role in the production of the Jovian aurora. A definitive answer to the question of the particles and processes involved in the production of the aurora at Jupiter, however, will require further remote-sensing observations in the different wavelength regimes as well as the measurements to be made by Galileo when it arrives at Jupiter in early 1992.

INTERPRETATION OF THE X-RAY OBSERVATIONS

As noted above, further evidence in support of the heavy ion precipitation process was provided by x-ray observations of the Jovian aurora carried out by Metzger et al. [1983]. The energy resolution of the Einstein x-ray observatory used in the observations was not sufficient to distinguish between a bremsstrahlung power law distribution and K-shell emission line spectra from sulfur and/or oxygen. However, based on modeling the K-shell and bremsstrahlung mechanisms and their convoluted response within the Einstein telescope, Metzger et al. [1983] inferred that the energy required to produce the observed x-ray emission by means of electron bremsstrahlung was unreasonably large compared with that required by the K-shell mechanism and thus argued in favor of heavy ion precipitation as the source of Jovian auroral x-rays.

The conclusions of Metzger et al. have been called into question recently by the work of Barbosa [1990]. Barbosa states that his

> "aim is to examine critically the conditions under which the x-ray observations of Metzger et al. [1983] can be plausibly accounted for in the framework of an electron excited aurora. We find that electron bremsstrahlung gives a most credible explanation of the x-ray data and one which is consistent with electron generation of UV, infrared, and radio emissions from the auroral regions as well. The main conclusion drawn from the analysis is that the precipitating auroral electrons should have a beamlike distribution with a bump on the tail in the maximum emissivity layer. This result implies the existence of field-aligned potential drops above the auroral region which give rise to characteristic electron energy spectra similar to those observed over the terrestrial

aurora [Frank and Ackerson, 1971]. The theory here relies heavily on auroral electron measurements made at Earth [Rees and Maeda, 1973] and corresponding theories of such measurements [Banks et al., 1974; Evans, 1974] for its proper interpretation in terms of primary and secondary auroral electrons."

The purpose of this Comment is to present electron transport calculations similar to those performed for the terrestrial aurora by Banks et al. [1974]. These calculations will demonstrate the inconsistency between the primary and secondary electron distribution parameters chosen by Barbosa [1990]. The decreased magnitude of secondary electron fluxes that result from calculations using the transport equations suggests that electron bremsstrahlung is not likely to be the source of Jovian x-rays, if terrestrial auroral electron theory is applicable.

THE MODEL

A self-consistent calculation of the primary and secondary precipitating electron distributions form the basis for the two-stream electron transport calculation used in the present model, which is derived from a Jovian auroral electron model introduced by Waite et al. [1983]. The model solves the one-dimensional chemical diffusion equations for atomic hydrogen, the major hydrocarbon species CH_4, C_2H_2, C_2H_4, C_2H_6, and CH_3, and the major ionospheric species H^+ and H_3^+. The neutral temperature structure adopted in the present study is an equatorial profile determined from the Voyager UVS occultation experiments [Festou et al., 1981]. Although auroral energy input is expected to modify this profile, there is at present little indication as to the effects of this input. Furthermore, increases in the auroral thermal structure produce little change in the calculations apart from changes in the relative altitude scale of the atmosphere. Hydrocarbon results are consistent with the recent work of Gladstone and Allen [private communication] using an eddy diffusion coefficient at the homopause (K_h) of 2×10^6 cm^2 s^{-1}. However, the presence of hydrocarbons has no effect on the present work apart from acting as an appropriate guide in determining the valid range of the primary electron beam parameters based on the relative absorption of H_2 band emissions by hydrocarbon species [Livengood et aL, 1990].

The auroral electron distributions as a function of altitude and energy are found by using a two-stream electron transport code modified for Jupiter [Waite et al., 1983] and extended to electron energies of 2 MeV using the relativistic H_2 cross sections of Garvey et al. [1977]. Input parameters of the primary incident electron distribution were chosen to be consistent with the cases A, B, C that were presented by Barbosa[1990] and are shown in Table 1. The differential bremsstrahlung cross sections were taken from the work of Koch and Motz [1959] (formulas 3BN and II-6). X-ray absorption effects were calculated, but were less than 10% at all photon energies above 100 eV for the primary electron beam cases considered (10 to 100 keV).

RESULTS AND DISCUSSION

The difference between the auroral electron distribution at the altitude of peak auroral energy dissipation and that assumed by Barbosa [1990] is shown in Figure 1. The Barbosa distribution is over 3 orders of magnitude different from that of the two-stream electron transport calculation at an electron energy of 1 keV. The theories of auroral electron measurements [e.g., Banks et aL, 1974] establish a strong correspondence between the primary electron beam parameters and the secondary beam parameters, since the secondary electron spectrum is created from ionization by the primary electron beam and the collective transport of the secondary electrons formed from this process. This suggests that there exists a strong coupling between the primary electron beam parameters and the secondary electron distribution parameters within the context of terrestrial auroral theory. However, this constraint is ignored in the calculations that are presented by Barbosa [1990]. Table 1 is a representation of the auroral electron distribution form and the free parameters for specifying the primary and secondary electron distribution function of Barbosa [1990]. The primary electron beam parameters in Babosa's study were chosen to represent both the total power constraints and the spectral characteristics of the observed H_2 band emissions [cf. Livengood et al., 1990]. The secondary electron distribution parameters were then independently chosen to satisfy the observed x-ray spectrum [Metzger et al., 1983], while at the same time being loosely constrained by the overall power dissipation of the observed Jovian auroral emissions. However, this independent specification of the primary and secondary electron distributions is inconsistent with theoretical [Banks et al., 1974] and observational [Fung and Hoffman, 1988] characteristics of the terrestrial aurora and corresponding electron transport calculations of the Jovian aurora presented in Figure 1.

X-ray flux as a function of photon energy as seen from Earth is shown in Figure 2. The solid lines indicate the two-stream calculation and the dotted lines the calculations of Barbosa [1990]. The observational data points of the Einstein Jovian x-ray observations are shown by the black dots with corresponding error bars. The excellent agreement of Barbosa [1990] is due to the arbitrary choice of the free parameters specifying the secondary electron distribution, the source of contention in the present Comment. Note that the x-ray spectrum produced by the two-stream model is both harder in spectral content and over an order of magnitude smaller in x-ray intensity in the region of the Einstein x-ray observations.

Similar calculations of the predicted Jovian x-ray production from bremsstrahlung electrons have also been carried out by Martin Walt [private communication 1991] using a more sophisticated model of the electron energy degradation and subsequent x-ray production [Walt et al., 1979]. The agreement between the Walt [private communication 1991] and Waite (this model) calculations is within a factor of 2 at all energies, assuming the same energetic electron spectrum [Barbosa, 1990] and the same neutral atmosphere model described in this paper.

CONCLUSIONS

Two possibilities appear to exist that could rescue the bremsstrahlung hypothesis of Jovian x-ray emissions: 1) the auroral electron energy flux during the Einstein observations exceeded 500 ergs cm^{-2} s^{-1}, a deviation of over 3 sigma from the average value as determined by Livengood et al. [1990], and 2) the Jovian auroral secondary electron spectrum is enhanced by over two orders of magnitude from that expected from degradation and ionization from auroral primary electrons; whereas the terrestrial analog suggests that standard electron-transport calculations explain observations of secondary electrons at Earth to better than 50% [Fung and Hoffman, 1988]. In addition to the changes required to increase the auroral x-ray intensity to the desired levels, the calculated bremsstrahlung x-ray flux also has a much harder x-ray spectrum than that observed by Einstein. Preferential forward scattering of electrons at higher energies (not incorporated in the present calculations, since isotropic emissions were assumed) would have a tendency to soften the spectrum, but even so, calculations by Martin Walt [private communication 1991] indicate that significant modifications to the auroral secondary electron spectrum would be required to produce the soft spectrum observed by Einstein.

Therefore, the results of the two-stream calculations reported here suggest that bremsstrahlung x-rays are not the likely source of Jovian x-ray emissions. However, ROSAT observations obtained in April, 1991 [Bagenal et al., 1989] should help to quantify and clarify the source of Jovian x-rays. ROSAT has over a factor of two increase in sensitivity and in energy resolution in the energy range of interest (up to 2 keV). Clearly, additional multispectral observations (x-ray, UV, IR), modeling, and *in situ* particle observations may be necessary to sort out the source of the Jovian auroral particles.

Table 1.

AURORAL ELECTRON BEAM MODELS

BARBOSA, JGR, 95(A9), 14969, 1990

$$J(E) = J_{os}\left(\frac{E_{os}}{E}\right)^{\gamma} e^{-E/E_{os}} + J_{op}\left(\frac{E}{E_{op}}\right) e^{-E/E_{op}}$$

$$\gamma = 2$$

CASE A

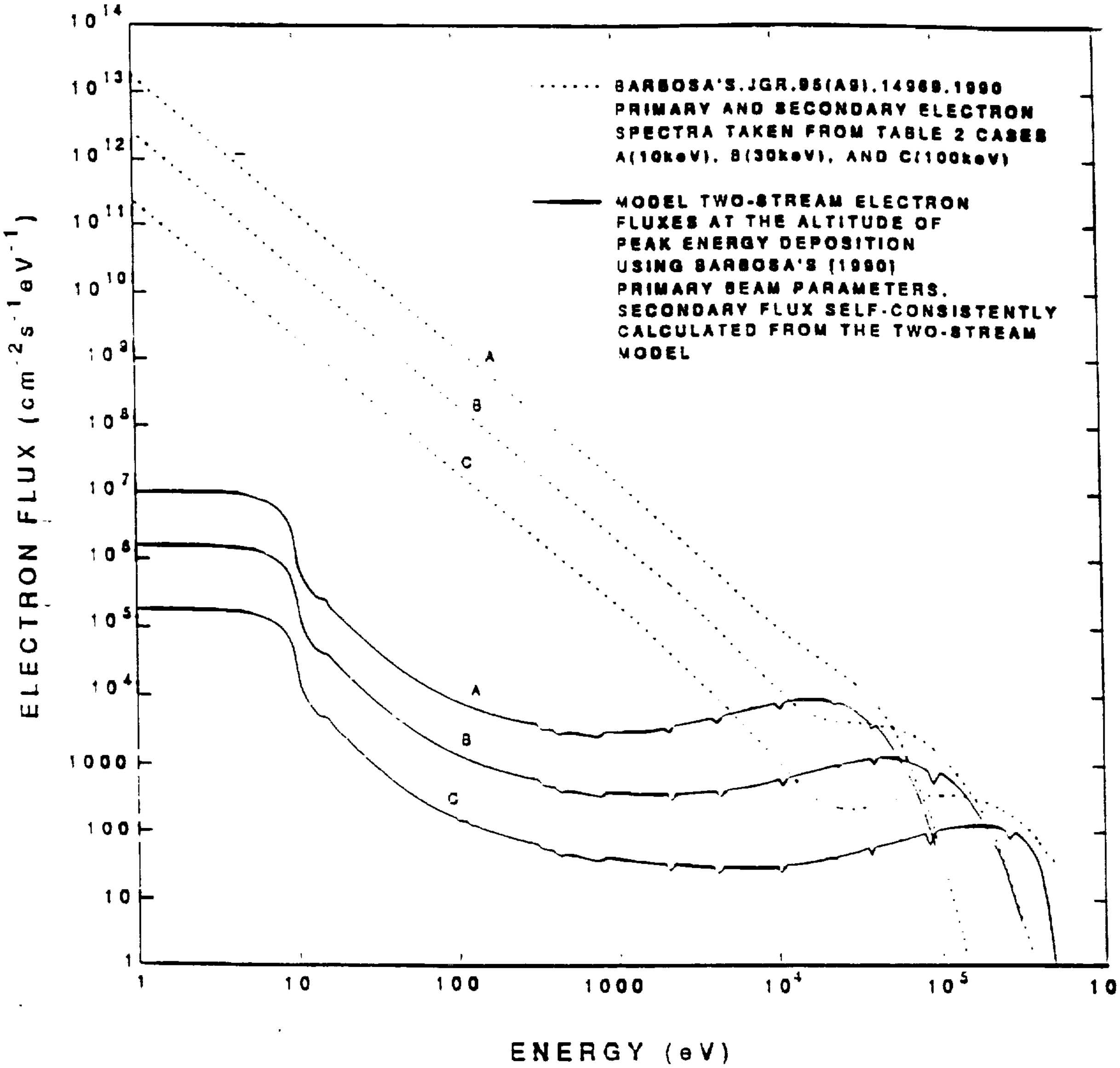
$E_{op} = (10 keV)$
$E_{os} = (10 keV)$
$J_{op} = 10^8 cm^{-2} s^{-1} keV^{-1}$
$J_{os} = 1.9 \times 10^8 cm^{-2} s^{-1} keV^{-1}$

CASE B

$E_{op} = (30 keV)$
$E_{os} = (10 keV)$
$J_{op} = 10^7 cm^{-2} s^{-1} keV^{-1}$
$J_{os} = 2.4 \times 10^7 cm^{-2} s^{-1} keV^{-1}$

CASE C

$E_{op} = (100 keV)$
$E_{os} = (10 keV)$
$J_{op} = 10^6 cm^{-2} s^{-1} keV^{-1}$
$J_{os} = 2.8 \times 10^6 cm^{-2} s^{-1} keV^{-1}$



BARBOSA'S JGR,95(A9),14969,1990
PRIMARY AND SECONDARY ELECTRON
SPECTRA TAKEN FROM TABLE 2 CASES
A(10keV), B(30keV), AND C(100keV)
MODEL TWO-STREAM ELECTRON
FLUXES AT THE ALTITUDE OF
PEAK ENERGY DEPOSITION
USING BARBOSA'S (1990)
PRIMARY BEAM PARAMETERS.
SECONDARY FLUX SELF-CONSISTENTLY
CALCULATED FROM THE TWO-STREAM
MODEL
ELECTRON FLUX (cm⁻² s⁻¹ eV⁻¹)
ENERGY (eV)
A
B
C

Figure 1.

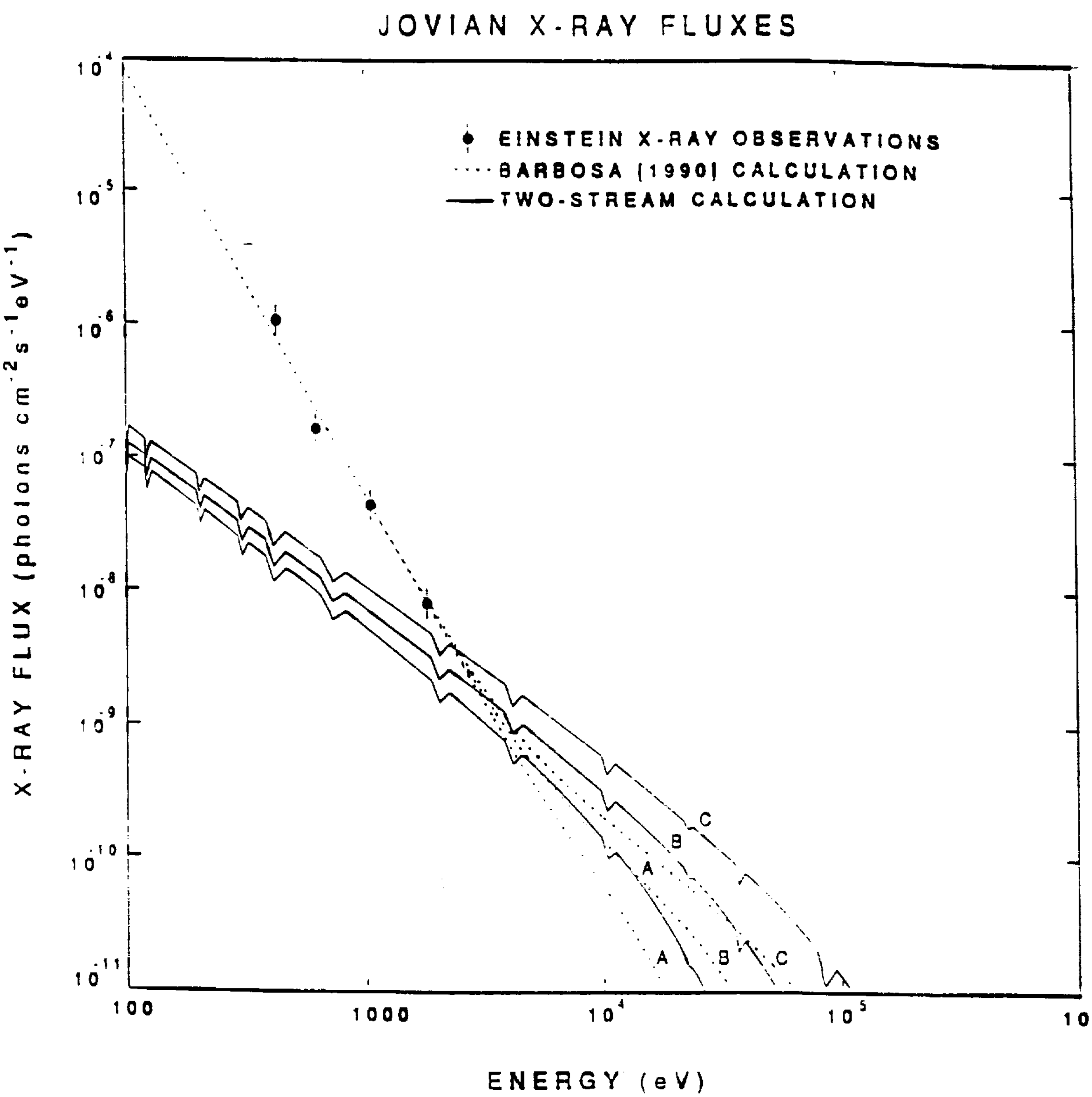

JOVIAN X-RAY FLUXES
EINSTEIN X-RAY OBSERVATIONS
BARBOSA (1990) CALCULATION
TWO-STREAM CALCULATION
X-RAY FLUX (photons cm-2 s-1 eV-1)
ENERGY (eV)
A
B
C
100
1000
10^4
10^5
10^6
10^-4
10^-5
10^-6
10^-7
10^-8
10^-9
10^-10
10^-11

Figure 2.

ACKNOWLEDGEMENT

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FIGURE CAPTIONS

Fig. 1: A plot of the differential electron flux as a function of electron energy. The dashed lines refer to cases A, B, and C from Barbosa [1990]. The solid lines are from calculations using the two-stream electron transport model of Waite (this paper) with initial electron fluxes at the top of the atmosphere set by the primary beam parameters of Barbosa's [1990] cases A, B, and C. The small drop outs in the

modeled electron fluxes are due to discrete changes in the energy bin structure and do not otherwise affect the results.

Fig. 2: A plot of the Jovian differential x-ray flux as a function of photon energy as viewed from an Earth orbiting observation platform such as Einstein. The Metzger et al. [1983] Einstein observations are shown by the data points and the empirical fit of Barbosa [1990] by the dashed line. Results of the self-consistent model of Waite (this paper) for input cases A, B, and C are shown by the solid lines. Again the discrete changes in the energy grid introduce small drop outs that do not otherwise affect the results.