## General Search Results--Full Record



**The photometric and spectroscopic characterization of the V Sagittae star V617 Sagittarii**

**Steiner JE**, Cieslinski D, Jablonski FJ, Williams RE

**ASTRONOMY AND ASTROPHYSICS**
351: (3) 1021-1027 NOV 1999

**Document type:** Letter **Language:** English Cited References: 38 Times Cited: 1

**Abstract:**
**Photometric** and spectroscopic characterization of the V Sge star V617 Sgr (WR 109) is presented. The orbital period, 0.207 day, is the shortest of its class. The optical light curve presents a double wave with minima and maxima of uneven brightness. Strong emission lines of highly ionized species such as HeII, NV and OVI dominate the optical spectrum. High and low **photometric** states have been observed and the primary eclipse becomes shallower at eruptions. H alpha emission becomes stronger and broader at high state when compared to low state. The striking similarities to V Sge are discussed. The **photometric** and spectroscopic observations suggest that a high and asymmetric rim exists associated with the accretion disk. This star is interpreted as a X-ray quiet galactic counterpart of the supersoft X-ray binaries seen in the Magellanic Clouds.

**Author Keywords:**
stars : novae, cataclysmic variables, stars : individual : V617 Sgr, stars : binaries : eclipsing, stars : Wolf-Rayet, X-rays : stars

**KeyWords Plus:**
WOLF-RAYET STARS, EQUATORIAL IRREGULAR VARIABLES, MACHO PROJECT PHOTOMETRY, OPTICAL VARIABILITY, SOUTHERN, BINARIES, EVOLUTION, LMC

**Addresses:**
Steiner JE, CNPq, Lab Nacl Astrofis, CP 21, BR-37500000 Itajuba, Brazil.
CNPq, Lab Nacl Astrofis, BR-37500000 Itajuba, Brazil.
Univ Sao Paulo, Inst Astron & Geofis, BR-01065970 Sao Paulo, Brazil.
Inst Nacl Pesquisas Espaciais, Div Astrofis, BR-12201970 Sao Jose Dos Campos, Brazil.
Space Telescope Sci Inst, Baltimore, MD 21218 USA.

**Publisher:**
SPRINGER VERLAG, NEW YORK

**IDS Number:**
262LG

**ISSN:**
0004-6361

# COMUT

## Solicitação Aguardando por Atendimento.

Número da Solicitação: 2220724/2001
Título da Revista: ASTRONOMY AND ASTROPHYSICS
Autor(es) do Artigo: STEINER, J.E., et al.
Título do Artigo: THE PHOTOMETRIC AND SPECTROSCOPIC...
Código CCN : XXXXXX
Volume: 351 Fascículo: 3 Suplemento: Fonte de Referência:
Data de Publicação: 1999

Página Inicial: 1021 Página Final: 1027 Total de Paginas: 07

Observações: IP: 150.163.34.21 MARCIANA - SID

Confirme o Total de Páginas: ______

Forma de Envio: Meio Eletrônico

Solicitante: 0081.7-INSTITUTO NACIONAL DE PESQUISAS ESPACIAIS-CENTRO DE INFORMAÇÃO E DOCUMENTAÇÃO
Enviar para.: 0081.7-INSTITUTO NACIONAL DE PESQUISAS ESPACIAIS-CENTRO DE INFORMAÇÃO E DOCUMENTAÇÃO

| | |
|---|---|
| Endereço de Envio: AV. DOS ASTRONAUTAS, 1758 | Bairro: JARDIM DA GRANJA |
| Cidade: SÃO JOSÉ DOS CAMPOS | UF: SP |
| CEP: 12201-970 | Telefone: |
| E-Mail: bteca@sid.inpe.br | Caixa Postal: 515 |

Atendimento de Solicitação

Repassar Solicitação | Cancela Solicitação

Retornar a Página Anterior

Astron. Astrophys. 351, 1021–1027 (1999)

ASTRONOMY AND ASTROPHYSICS

# The photometric and spectroscopic characterization of the V Sagittae star V617 Sagittarii*

J.E. Steiner[1,2], D. Cieslinski[3], F.J. Jablonski[3], and R.E. Williams[4]

[1] Laboratório Nacional de Astrofísica/CNPq, CP 21, 37500-000 Itajubá, Brazil
[2] Instituto Astronômico e Geofísico, Universidade de São Paulo, CP 9638, 01065-970 São Paulo, Brazil
[3] Divisão de Astrofísica, Instituto Nacional de Pesquisas Espaciais, CP 515, 12201-970 São José dos Campos, Brazil
[4] Space Telescope Science Institute–STScI, 3700 San Martin Drive, Baltimore, MD 21218, USA

Received 11 June 1999 / Accepted 15 September 1999

**Abstract.** Photometric and spectroscopic characterization of the V Sge star V617 Sgr (WR 109) is presented. The orbital period, 0.207 day, is the shortest of its class. The optical light curve presents a double wave with minima and maxima of uneven brightness. Strong emission lines of highly ionized species such as HeII, NV and OVI dominate the optical spectrum. High and low photometric states have been observed and the primary eclipse becomes shallower at eruptions. Hα emission becomes stronger and broader at high state when compared to low state. The striking similarities to V Sge are discussed. The photometric and spectroscopic observations suggest that a high and asymmetric rim exists associated with the accretion disk. This star is interpreted as a X-ray quiet galactic counterpart of the supersoft X-ray binaries seen in the Magellanic Clouds.

**Key words:** stars: novae, cataclysmic variables – stars: individual: V617 Sgr – stars: binaries: eclipsing – stars: Wolf-Rayet – X-rays: stars

## 1. Introduction

In the course of a photometric and spectroscopic survey of southern and equatorial irregular variables (Steiner et al. 1988; Cieslinski et al. 1997; Cieslinski et al. 1998) we have observed V617 Sgr, a star classified as an irregular variable of type I in the General Catalogue of Variable Stars (Kholopov et al. 1987). It became evident that this star had been misclassified, having a spectrum very similar to V Sge and an orbital period of about 5 hours (Steiner et al. 1988). Later we found that this object was also classified as a Wolf-Rayet star – WR 109 in the catalog of van der Hucht et al. (1981). Van der Hucht et al. (1988) and Conti & Vacca (1990) classified the object as WN3. The later authors suggested a distance of 32.5 kpc under the hypothesis that it is a normal WR star. Such classification was challenged by Lundström & Stenholm (1984, 1989) on the basis of the small observed extinction. Recently, Steiner & Diaz (1998) included this star in a group of 4 objects called the V Sagittae stars and suggested that this class might be the galactic counterpart of the Compact Binary Supersoft Sources seen in the Magellanic Clouds (Kahabka & van den Heuvel 1997).

In the present paper we report on the photometric and spectroscopic characterization of V617 Sgr and discuss its implications and similarities with other stars. A detailed spectroscopic study using Doppler Tomography was presented in a separate paper (Cieslinski et al. 1999 – CDS).

## 2. Observations and data reduction

### 2.1. Photometry

V617 Sgr was monitored on various occasions at the Laboratório Nacional de Astrofísica – CNPq/LNA in southeast Brazil. Photoelectric measurements were made with an offset-guided photometer (FOTEX) and with the FOTRAP photometer (Jablonski et al. 1994) on the 1.6-m and 0.6-m telescopes. CCD photometry was obtained at the 0.6-m telescopes using two LNA's CCD and the CCD photometer. Both configurations use Wright Instruments Ltd cameras. The CCD's used were a GEC P8603 front-illuminated chip (CCD 009) and a SITeSI003AB back-illuminated chip (CCD 101), while the CCD photometer is equipped with a EEV CCD-02-06-1-206 back-illuminated chip specially prepared for high time resolution observations. The journal of observations is shown in Table 1.

Absolute photoelectric photometry was obtained on 8 occasions using UBV filters. These measurements are shown in Table 2. Typical errors in these measurements are 0.02 magnitudes in V, 0.03 in B−V and 0.08 in U−B. The median values are V=14.72, B−V=−0.05 and U−B=−0.79. For nights in which no absolute photometric calibration was available, the UBV magnitudes were obtained differentially by measuring a nearby (94″ East and 121″ South) comparison star of magnitude V=12.22 and colors B−V=0.64 and U−B=0.16.

*Send offprint requests to*: J.E. Steiner (steiner@lna.br)

* Based on observations made at Laboratório Nacional de Astrofísica/CNPq, Brazil, and Cerro Tololo Interamerican Observatory–CTIO, Chile.

**Table 1.** Journal of time series photometry of V617 Sgr

| Date | Start HJD (2440000+) | Δt(s) | Filter[a] | Length (hrs) | Instrument (detector) |
|---|---|---|---|---|---|
| 1987 Mar 23 | 6877.80362 | 10 | C | 0.90 | FOTEX |
| 1987 Mar 24 | 6878.71891 | 10 | C | 1.51 | FOTEX |
| 1987 Jun 01 | 6947.74183 | 10 | C | 2.70 | FOTEX |
| 1987 Jun 06 | 6952.71270 | 10 | C | 3.44 | FOTEX |
| 1987 Jun 26 | 6972.53457 | 31.3 | U,B,V | 1.11 | FOTEX |
| 1987 Jun 26 | 6972.64055 | 31.3 | U,B,V | 1.41 | FOTEX |
| 1987 Jun 27 | 6973.45730 | 16.3 | U,B,V | 8.97 | FOTEX |
| 1987 Jun 28 | 6974.42777 | 16.3 | U,B,V | 2.16 | FOTEX |
| 1987 Jun 30 | 6976.49277 | 1 | C | 0.66 | FOTEX |
| 1987 Jun 30 | 6976.59881 | 17.3 | U,B,V | 3.12 | FOTEX |
| 1987 Jul 01 | 6977.53715 | 1 | C | 0.64 | FOTEX |
| 1989 May 11 | 7657.75741 | 180 | C | 2.36 | CCD 009 |
| 1989 May 12 | 7658.72302 | 180 | C | 3.05 | CCD 009 |
| 1989 Jul 07 | 7721.51408 | 300 | C | 6.96 | CCD 009 |
| 1989 Jul 18 | 7725.51396 | 240 | C | 6.82 | CCD 009 |
| 1990 May 25 | 8036.78747 | 180 | R | 1.77 | CCD 009 |
| 1990 Jun 27 | 8069.64362 | 180 | C | 4.50 | CCD 009 |
| 1997 Jun 03 | 10602.55213 | 1 | C | 3.16 | CCD 301 |
| 1997 Aug 10 | 10671.49039 | 10 | R | 6.21 | CCD 301 |
| 1998 Jul 16 | 11011.53858 | 10 | R | 6.76 | CCD 301 |
| 1998 Jul 17 | 11012.59656 | 10 | R | 3.89 | CCD 301 |
| 1998 Jul 18 | 11013.57336 | 10 | R | 4.69 | CCD 301 |
| 1998 Aug 14 | 11040.47981 | 40 | V | 3.60 | CCD 101 |
| 1998 Aug 15 | 11041.47752 | 40 | V | 4.97 | CCD 101 |
| 1999 Apr 22 | 11290.77878 | 30 | V | 1.72 | CCD 101 |
| 1999 Apr 24 | 11292.63687 | 20 | V | 2.83 | CCD 301 |

[a] C = integral light, R = Cousin filter, UBV = Johnson filters

**Table 2.** UBV photometry of V617 Sgr

| JD | V | U−B | B−V |
|---|---|---|---|
| 2446650.6023 | 14.82 | −0.82 | 0.16 |
| 2446877.8020 | 15.15 | −0.87 | −0.01 |
| 2446947.7296 | 14.68 | −0.72 | 0.05 |
| 2446952.7061 | 14.73 | −0.79 | −0.01 |
| 2446966.5388 | 14.62 | −0.76 | 0.03 |
| 2446966.5445 | 14.64 | −0.84 | −0.07 |
| 2446966.5514 | 14.59 | −0.80 | −0.04 |
| 2446966.5648 | 14.68 | −0.89 | −0.10 |
| 2446966.5697 | 14.64 | −0.82 | −0.07 |
| 2446966.5747 | 14.72 | −0.92 | −0.11 |
| 2446966.5790 | 14.69 | −0.78 | −0.08 |
| 2446966.5835 | 14.66 | −0.72 | −0.04 |
| 2446966.5944 | 14.78 | −0.78 | −0.06 |
| 2446966.6280 | 14.76 | −0.74 | 0.04 |
| 2446966.6428 | 14.68 | −0.72 | −0.03 |
| 2446966.6479 | 14.76 | −0.73 | −0.01 |
| 2446966.6755 | 14.58 | −0.81 | −0.08 |
| 2446966.6896 | 14.77 | −0.89 | −0.07 |
| 2446966.7091 | 14.73 | −0.71 | −0.06 |
| 2446966.7140 | 14.72 | −0.74 | 0.01 |
| 2446966.7276 | 14.69 | −0.73 | −0.04 |
| 2446966.7318 | 14.76 | −0.75 | −0.09 |
| 2446976.4636 | 14.89 | −0.76 | −0.05 |
| 2446976.5220 | 14.73 | −0.81 | −0.07 |
| 2446977.5302 | 14.61 | −0.81 | −0.04 |
| 2447004.4744 | 14.78 | −0.83 | −0.12 |
| 2447361.4501 | 14.47 | −0.83 | −0.03 |

### 2.2. *Spectroscopy*

Spectroscopic observations of V617 Sgr were carried out in 1986 June/July with the 2D Frutti photon-counting detector on the Cassegrain Spectrograph at the 1 meter telescope of Cerro Tololo Interamerican Observatory (CTIO). The observations covered the wavelength range of 3900–6800 Å with 5 Å resolution. Spectrophotometric standard stars were observed, providing an accuracy of about 30% in absolute fluxes. The average spectrum is shown in Fig. 1 while the equivalent widths and fluxes of the most conspicuous emission lines are listed in Table 4.

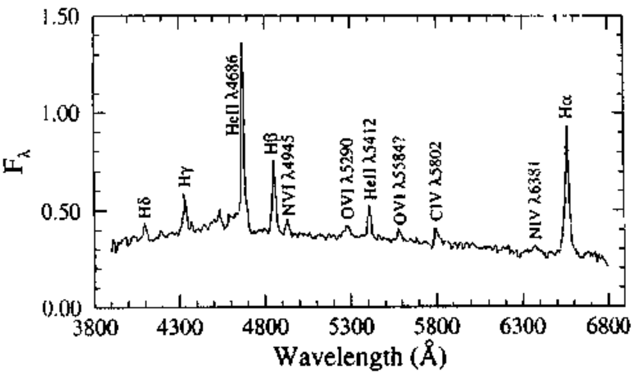


**Fig. 1.** The CTIO average spectrum of V617 Sgr. The FWHM resolution is 5 Å and flux is in units of $10^{-14}$ erg cm$^{-2}$ s$^{-1}$ Å$^{-1}$.

V617 Sgr was also observed with the 1.6-m telescope at Laboratório Nacional de Astrofísica. On June 30, 1989 (UT) it was observed with a Coudè spectrograph + GEC CCD and a 600 lines/mm grating. A total of 15 spectra with integration times of 10 and 15 minutes were collected. The spectral resolution was 1 Å. On Apr 15, 1997 (UT) we observed V617 Sgr at Hα using the Cassegrain spectrograph, a front-illuminated and UV-coated GEC P88230 CCD (770×1152 pixels) as detector and a 1200 lines/mm grating. The spectral resolution provided by this instrumental configuration is 2 Å. A near infrared 10 Å resolution spectrum was also obtained on Feb 22, 1996 (UT), with a 300 lines/mm grating, the CCD SITe and an order sorting OG550 filter. This filter has a transmission of less than 0.05% at 5300 Å. Another spectrum in the Hα region was obtained on Aug 13, 1998 (UT) with Cassegrain spectrograph. In this case we used a 600 lines/mm grating and the detector CCD SITe, which provided a resolution of 5 Å. The Hα line properties are summarized in Table 5.

## 3. Data analysis

### 3.1. *The light curve*

The dominant characteristic of the light curve is a strong modulation with two minima of distinct depth per cycle. The

**Table 3.** Times of minima

| Day | Filter | $\Delta m$ | E | Instrument (detector) |
|---|---|---|---|---|
| 2446878.773(±1) | C | 0.5: | 0 | FOTEX |
| 2446947.758(±1) | C | 0.75 | 333 | FOTEX |
| 2446952.731(±4) | C | 0.35 | 357 | FOTEX |
| 2446973.655(±1) | B | 0.65 | 458 | FOTEX |
| 2446974.483(±1) | B | 0.4: | 462 | FOTEX |
| 2447658.754(±3) | C | 0.42 | 3765 | CCD 009 |
| 2447721.733(±5) | C | 0.10 | 4069 | CCD 009 |
| 2447725.670(±2) | C | 0.30 | 4088 | CCD 009 |
| 2448036.829(±3) | R | 0.63 | 5590 | CCD 009 |
| 2448069.768(±4) | C | 0.46 | 5749 | CCD 009 |
| 2450246.685(±6) | Spec[a] | 1.0: | 16257 | CCD 101 |
| 2450602.595(±4) | C | 0.43 | 17975 | CCD 301 |
| 2450671.582(±2) | R | 0.39 | 18308 | CCD 301 |
| 2451011.754(±1) | R | 0.25 | 19950 | CCD 301 |
| 2451013.615(±1) | R | 0.50 | 19959 | CCD 301 |
| 2451040.541(±1) | V | 0.36 | 20089 | CCD 101 |
| 2451041.577(±1) | V | 0.28 | 20094 | CCD 101 |
| 2451290.806(±3) | V | 0.45 | 21297 | CCD 101 |
| 2451292.669(±2) | V | 0.65: | 21306 | CCD 301 |

[a] Time of minimum obtained from synthetic photometry of spectra

**Table 4.** Equivalent widths and fluxes of emission lines

| Line | $W_\lambda$(Å) | $F_\lambda$ ($\times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$) |
|---|---|---|
| Hγ | 15 | 5.9 |
| HeII λ4540 | 21 | 8.4 |
| HeII λ4686 | 70 | 28.5 |
| Hβ | 27 | 11.2 |
| NV λ4933 | 6 | 2.3 |
| OVI λ5282 | 4 | 1.7 |
| HeII λ5412 | 9 | 3.6 |
| OV λ5590 | 4 | 1.7 |
| CVI λ5805 | 6 | 2.3 |
| Hα | 70 | 22.4 |

**Table 5.** Hα properties

| Date | W(Hα) (Å) | FWHM (km s$^{-1}$) | FWZI (km s$^{-1}$) | Origin |
|---|---|---|---|---|
| 1986 June/July | 70 | 1030 | 3700 | CTIO[a] |
| 1989 Jun 30 | 288 | 2900 | 5400 | LNA/Coudè[a] |
| 1996 Feb 22 | 85 | 1300 | 3500 | LNA/NIR[b] |
| 1997 Apr 15 | 148 | 1600 | 6600 | LNA[c] |
| 1998 Aug 13 | 155 | 1065 | 4830 | LNA[d] |

[a] Average spectra
[b] Cassegrain, 300 lines/mm grating
[c] Cassegrain, 1200 lines/mm grating
[d] Cassegrain, 600 lines/mm grating

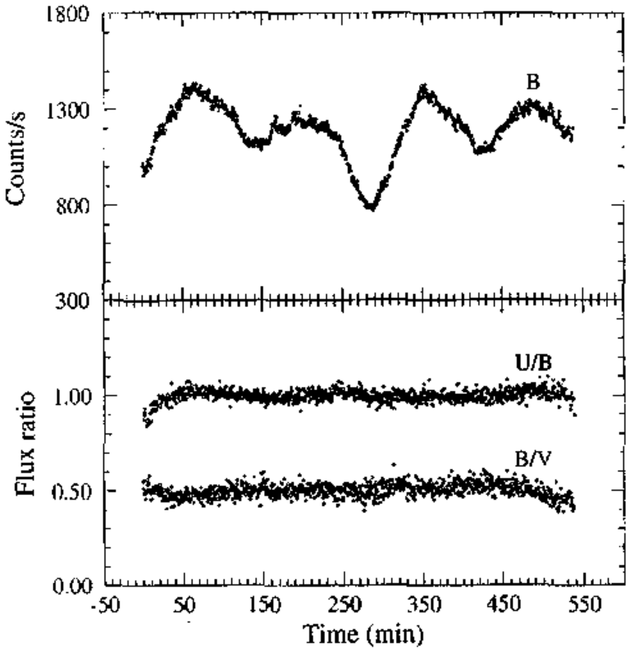


**Fig. 2.** Light curve of one night showing the eclipse 458.

ephemeris for the primary (deepest – see Table 3) minimum is

$$T_{min}(HJD) = 2446878.772(\pm 1) + 0.2071667(\pm 3) \times E \quad (1)$$

Fig. 2 shows a light curve from a single night while Fig. 3 shows the superimposed light curves of distinct nights normalized to the average of each night. We will call the deepest minimum as the primary eclipse and the secondary minimum as the secondary eclipse. By definition of the Eq. (1) the center of the primary eclipse occurs at $\phi$=0. This eclipse has a V shape and the minimum light can be determined with an accuracy of ±2 minutes. The secondary eclipse is not centered at phase 0.5 but at $\phi \simeq 0.57$. In Fig. 2 it has a flat bottom shape that last for about $\Delta\phi \simeq 0.15$. On the average, the primary eclipse is about 0.17 magnitudes deeper than the secondary one. The primary maximum is centered at $\phi \simeq 0.28$ while the secondary maximum, at $\phi \simeq 0.75$. The primary maximum is about 0.1 magnitudes brighter than the secondary one. An interesting characteristic of the light curve is that both primary minimum *and* maximum show larger scatter of depth and height than secondary ones.

The fact that the secondary eclipse is not centered at phase 0.5 in binary systems is usually considered evidence of an eccentric orbit. For the present star, this is not likely to be the case. As shown from the spectroscopic evidence (CDS), the region of the hot spot has strong emission of HeII and self absorption in Hβ. This suggests the existence of a high asymmetric rim over the disk, similar to the proposed ones for the CBSS (Meyer-Hofmeister et al. 1997). Such a rim + hot spot are likely to be the occultation source for the secondary eclipse. The (optically thick) rim illumination by the central source may also produce a source of optical continuum light brighter at phase 0.25 than at phase 0.75 (see Fig. 6). Evidence for this is also seen in the spectroscopic analysis (CDS). A qualitative inspection of the light curve of V617 Sgr shows a surprising similarity to CAL 87 (Meyer-Hofmeister et al. 1997), V Sge (Patterson et al. 1998) and QR And (Meyer-Hofmeister et al. 1998).

Patterson J., 1984, ApJS 54, 443
Patterson J., Kemp J., Shambrook A., et al., 1998, PASP 110, 380
Rappaport S.D., Di Stefano R., Smith J.D., 1994, ApJ 426, 692
Rauw G., Gosset E., Manfroid J., Vreux J.-M., Claeskens J.F., 1996, A&A 306, 783
Robertson J.W., Honeycutt K.R., Pier J.R., 1997, AJ 113, 787
Simon V., 1996, A&AS 118, 421
Southwell K.A., Livio M., Charles P.A., O'Donoghue D., Sutherland W.J., 1996, ApJ 470, 1065
Steiner J.E., Cieslinski D., Jablonski F.J., 1988, In: Blanco V.M., Phillips M.M. (eds.) Progress and Opportunities in Southern Hemisphere Optical Astronomy. ASP Conf. Ser. 1, 67
Steiner J.E., Diaz M.P., 1998, PASP 110, 276
Warner B., 1995, In: Cataclysmic Variable Stars. Cambridge University Press, Cambridge
Williams R.E., Ferguson D.H., 1983, In: Livio M., Shaviv G. (eds.) Cataclysmic Variables and Related Objects. IAU Coll. 72, Reidel, Dordrecht, p. 97

## General Search Results--Full Record



**A broadband theory of Langmuir-whistler events in the solar wind**

Luo QH, Chian ACL, Borotto FA

ASTRONOMY AND ASTROPHYSICS
348: (1) L13-L16 AUG 1999

**Document type:** Letter **Language:** English Cited References: 26 Times Cited: 2

**Abstract:**
Recent interplanetary observations presented evidence of simultaneous excitation of high-frequency Langmuir waves and low-frequency electromagnetic whistler waves in the magnetic holes of the solar wind. In this letter, we formulate a **broadband** theory of the interplanetary Langmuir-whistler events. We show that whistler waves can grow exponentially as a result of nonlinear interactions of Langmuir waves and left-hand circularly polarized radio waves. In particular, the growth of whistler waves favors propagation parallel to the Langmuir waves.

**Author Keywords:**
plasmas, Sun : solar wind, turbulence

**KeyWords Plus:**
MIRROR-MODE STRUCTURES, MAGNETIC HOLES, RADIO-BURSTS, PHOTON-BEAM, WAVES, PLASMA, GENERATION, RADIATION

**Addresses:**
Luo QH, Univ Adelaide, Dept Phys & Math Phys, Adelaide, SA 5005, Australia.
Univ Adelaide, Dept Phys & Math Phys, Adelaide, SA 5005, Australia.
Univ Adelaide, CSSM, Adelaide, SA 5005, Australia.
Natl Inst Space Res, BR-12201970 Sao Jose Dos Campos, Brazil.
Concepcion Univ, Dept Fis, Concepcion, Chile.

**Publisher:**
SPRINGER VERLAG, NEW YORK

**IDS Number:**
225ZD

**ISSN:**
0004-6361

# COMUT
## Solicitação de Artigo de Revista

**O Número de seu pedido é: 2220730 /2001**

**Código CCN :** XXXXXX

**Título da Revista:** ASTRONOMY AND ASTROPHYSICS

**Autor(es) do Artigo :** LUO, Q., CHIAN, A.C.L.; e **Título do Artigo:** A BROADBAND THEORY OF ...

**Ano Publ:** 1999 **Vol:** 348 **Fasc:** ?? **Supl:** **Fonte Ref:**

**Página Inicial:** L13 **Página Final:** L16 **Total de Páginas:** 04

**Observações:**
IP: 150.163.34.21
MARCIANA - SID

**Forma de Envio:** Meio Eletrônico **Categoria Usuário:** Outros

**Nome do Usuário:** MARCIANA

**Opções de Bibliotecas para Atendimento:**

1- RS/UFRGS/IFIS/BT-UNIVERSIDADE FEDERAL DO RIO GRANDE DO SUL-INSTITUTO DE FÍSICA-BIBLIOTECA

2-

3-

**Preencha Somente se desejas enviar para casa do Usuário Solicitante:**

**Endereço:** **Bairro:**

**Cidade:** **UF:**

**CEP:** **Tel:**

**E-Mail:**

Enviar Solicitação | Limpa Formulário

Retornar ao Menu Principal

Astron. Astrophys. 348, L13–L16 (1999)

ASTRONOMY
AND
ASTROPHYSICS

*Letter to the Editor*

# A broadband theory of Langmuir-whistler events in the solar wind

**Qinghuan Luo[1,*], Abraham C.-L. Chian[2,3], and Félix A. Borotto[2,3,4]**

[1] Department of Physics and Mathematical Physics, University of Adelaide, SA 5005, Australia
[2] CSSM, University of Adelaide, SA 5005, Australia
[3] National Institute for Space Research (INPE), P.O. Box 515, 12201-970 São José dos Campos – SP, Brazil
[4] Departamento de Física, Universidad de Concepción, Concepción, Chile

Received 7 June 1999 / Accepted 19 June 1999

**Abstract.** Recent interplanetary observations presented evidence of simultaneous excitation of high-frequency Langmuir waves and low-frequency electromagnetic whistler waves in the magnetic holes of the solar wind. In this letter, we formulate a broadband theory of the interplanetary Langmuir-whistler events. We show that whistler waves can grow exponentially as a result of nonlinear interactions of Langmuir waves and left-hand circularly polarized radio waves. In particular, the growth of whistler waves favors propagation parallel to the Langmuir waves.

**Key words:** plasmas – Sun: solar wind – turbulence

## 1. Introduction

Ulysses observation of high-frequency electrostatic Langmuir waves in close temporal correlation with low-frequency electromagnetic whistler waves suggests that nonlinear coupling between these two types of plasma waves may occur in the solar wind (Kellogg et al. 1992; Lin et al. 1995; Stone et al. 1995). These interplanetary Langmuir-whistler events were seen within the local depressions of solar wind magnetic field known as magnetic holes. A theoretical model was proposed by Chian & Abalde (1999) to describe the nonlinear interaction between Langmuir waves and whistler waves in the solar wind. In their model the pump is the Langmuir wave, whereas whistler waves and circularly polarized radio waves are produced through three-wave interactions. Their model was based on the fixed-phase formalism, which is applicable only to narrowband waves with the associated bandwidth less than the growth rate. Fixed-phase analysis of nonlinear Langmuir-whistler mode coupling has also been considered by Hasegawa (1974) and Novikov et al. (1976). In addition, parametric interactions of Langmuir waves and circularly polarized electromagnetic waves have been studied by Stenflo (1970), Larsson & Stenflo (1973), Shukla & Sharma (1982), Chian, Lopes & Alves (1994), Stenflo & Shukla (1995) and Chian et al. (1997). In the solar wind, nonlinear wave-wave interactions often occur in the broadband regime whereby the bandwidth of growing waves is greater than the growth rate. The aim of this paper is to perform a random-phase analysis of nonlinear coupling of Langmuir waves with whistler waves in order to extend the validity of the interplanetary Langmuir-whistler model of Chian and Abalde (1999) to the regime of broadband waves.

*Send offprint requests to*: Q. Luo (luo@physics.usyd.edu.au)
* *Present address:* SRCfTA, School of Physics, University of Sydney, NSW 2006, Australia.

## 2. Theory

We consider three-wave interactions among Langmuir wave ($L$), right- and left-hand circularly polarized radio waves ($r$, $l$), and electromagnetic whistler wave ($W$) in the weak turbulence approximation, in which the growth rate of any wave is much less than the reciprocal of the lowest frequency of the three waves. We discuss specifically the following two three-wave processes: $L \rightleftarrows l + W$, and $L + W \rightleftarrows r$, with the frequencies and wave numbers satisfying the conditions, $\omega = \omega_1 + \omega_2$, $\mathbf{k} = \mathbf{k}_1 + \mathbf{k}_2$ ($l$-waves); $\omega_1 = \omega + \omega_2$, $\mathbf{k}_1 = \mathbf{k} + \mathbf{k}_2$ ($r$-waves), where $(\mathbf{k}, \omega)$, $(\mathbf{k}_1, \omega_1)$, $(\mathbf{k}_2, \omega_2)$ are the wave vectors and frequencies of the $L$, $r$ (or $l$) and $W$ waves. Examples of three-wave interactions (forward-scattering) are shown in Fig. 1.

In the random-phase approximation, waves are regarded as a collection of quanta with occupation number represented by $N(\mathbf{k})$, and wave-wave interaction is then described by a set of kinetic equations for $N(\mathbf{k})$ for various waves involved [for a detailed discussion see Davidson (1972), Tsytovich (1972) and Melrose (1986a,b)]. To estimate the growth rate of whistler waves, it is convenient to consider the kinetic equations in the form similar to radiative transfer equations (Luo & Melrose 1995, 1997; Luo & Chian 1997),

$$\frac{dN_W(\mathbf{k}_2)}{dt} = -\Gamma_W^{(\pm)} N_W(\mathbf{k}_2) + S_W^{(\pm)}(\mathbf{k}_2), \tag{1}$$

where $\pm$ correspond respectively to $r$- and $l$-polarization, and

$$\Gamma_W^{(\pm)} = -\int \frac{d^3k}{(2\pi)^3} u_{LW}^{(\pm)} \left[\pm N_\pm(\mathbf{k}_1) \mp N_L(\mathbf{k})\right], \tag{2}$$

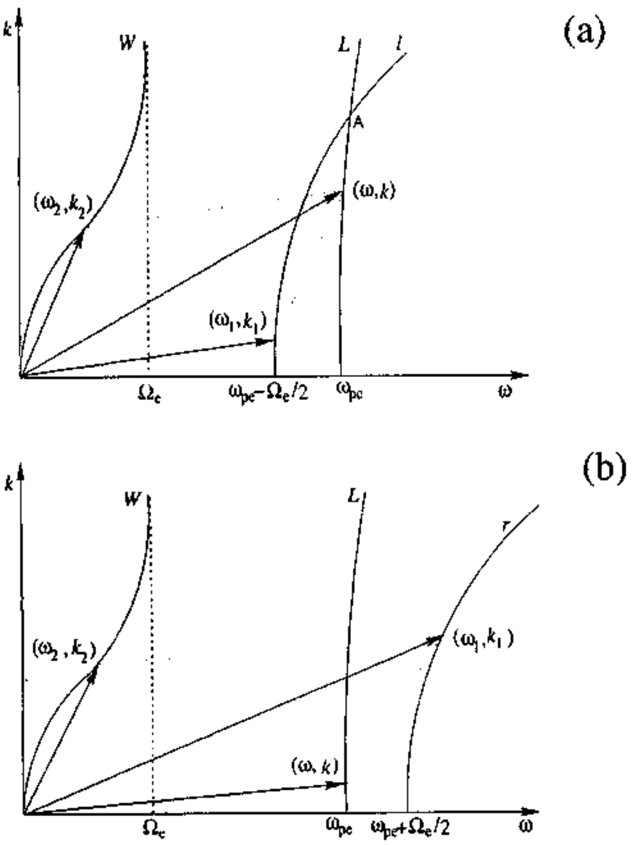


**Fig. 1a and b.** Three-wave conditions. **a**: $\omega = \omega_1 + \omega_2$, $k = k_1 + k_2$ with $\omega \approx \omega_1 \gg \omega_2 \approx \Omega_e/2$, $k \approx k_2 \gg k_1$. **b**: $\omega_1 = \omega + \omega_2$, $k_1 = k + k_2$ with $\omega \approx \omega_1 \gg \omega_2 \approx \Omega_e/2$, $k_1 \approx k_2 \gg k$.

is the nonlinear absorption coefficients, and

$$S_W^{(\pm)} = \int \frac{d^3k}{(2\pi)^3} u_{LW}^{(\pm)} N_L(\mathbf{k}) N_\pm(\mathbf{k}_1). \tag{3}$$

describes emission of whistler waves as a result of induced decay of $L$ into $l$ (or $r$ into $L$), where $\mathbf{k}_1 = \mathbf{k} \pm \mathbf{k}_2$, $u_{LW}^{(\pm)}$ is the three-wave probability. The absorption coefficient (2) can be negative, corresponding to wave growth. So, $\Gamma_W^{(\pm)}$ is sometimes referred to as the damping (growth) rate.

We assume that Langmuir waves, which act as the pump, are produced mainly through a beam-plasma instability, which can be the case in the solar wind, and that $N_L > N_\pm$. Then, we have nonlinear growth of whistler waves, $\Gamma_W^{(-)} < 0$, as a result of the pump depletion through three-wave interaction $L \rightleftarrows l + W$. Similarly, we have nonlinear damping, $\Gamma_W^{(+)} > 0$, through $L + W \rightleftarrows r$. The two processes compete with each other.

The essential part of the calculation of $\Gamma_W^{(\pm)}$ is the derivation of the three-wave probability. Here we write down the probability for parallel propagation and forward-scattering ($k_{2z} > 0$),

$$u_{LW}^{(\pm)} = r_e c^2 R_W \left(\frac{\pi^2 \hbar \omega_2}{2m_e c^2}\right) \frac{\omega_1 \omega_{pe}^2}{\omega} \left(\frac{n_\pm}{\omega_2 - \Omega_e} \mp \frac{n_W}{\omega_1 \mp \Omega_e}\right)^2 \times \delta(\omega - \omega_1 \pm \omega_2), \tag{4}$$

where $\omega_{pe}$ is the plasma frequency, $\Omega_e$ is the cyclotron frequency, $R_W$ is the ratio of electric to magnetic energy denisty in the whistler waves, $r_e = e^2/4\pi\varepsilon_0 m_e c^2$ is the classical radius of electron, $n_\pm$ and $n_W$ are the refraction indices. A similar form can be derived for back-scattering ($k_{2z} < 0$) by replacing $n_W \to -n_W$. We assume $N_L(k)$ is peaked at $k_0$ with a spread, $\Delta k < k_0$, where $k_0$ satisfies $\xi(k_0) \equiv \omega(k_0) - \omega_1(k_0) \pm \omega_2(k_0) = 0$. Because $\Gamma_W^{(\pm)} \propto 1/|\xi'|$, the growth rate must peak at $|\xi'| \approx 0$.

For $n_\pm \gg 3\beta_{\rm th}^2 n_L = 2\times 10^{-5} n_L(T_e/4\times 10^4\,{\rm K})$, we have $|\xi'| \approx c n_\pm$. Assuming $n_W^2/(\omega_1 \mp \Omega_e)^2 \gg n_\pm^2/(\omega_2 - \Omega_e)^2$ (when either $\omega_2 \ll \Omega_e$ or $n_\pm \ll 1$) and using (4), we obtain

$$\Gamma_W^{(\pm)} \approx \pm 2\pi^2 r_e c^2 \frac{W_L}{\Delta n_L n_\pm} \frac{\omega_2}{\omega^2} \left(1 - \frac{\omega_2}{\Omega_e}\right), \tag{5}$$

where $W_L \approx (\Delta k/2\pi)\hbar\omega\, N_L(k)/m_e c^2$ is the the energy density in Langmuir waves, $\Delta n_L = \Delta k c/\omega$, we neglect the difference between $u_{LW}^{(+)}$ and $u_{LW}^{(-)}$ which is of the order magnitude $\Omega_e/\omega$. In general, $\Gamma_W^{(+)} \neq -\Gamma_W^{(-)}$, i.e. in some parameter regions, one dominates the other.

One can calculate the growth rate for circularly polarized radio waves by writing the relevant kinetic equations into the form similar to Eq. (1), i.e. $N_W \to N_\pm$, $\Gamma_W^{(\pm)} \to \Gamma_\pm$ (the absorption coefficients for $r$-, $l$-waves), $S_W^{(\pm)} \to S_\pm$ (stimulated emission of $r$-waves as a result of induced fusion of $L$ with $W$, and stimulated emission of $l$-waves due to induced decay of $L$ into $W$). Similarly to whistler waves, $l$-waves can grow exponentially, provided that $N_L \gg N_W$. However, the absorption coefficient $\Gamma_+(\mathbf{k}_1)$ is always positive, and hence $r$-waves can only be produced through fusion of $L$ with $W$.

For $N_L \gg N_W$, $\Gamma_\pm$ can be written into the form similar to Eq. (5) but with $|\xi'| = |d\omega/dk \pm d\omega_2/dk|$. When $\omega_2$, $\Omega_e$ are not too small, i.e., they satisfy the condition $\omega_2\Omega_e/\omega_{pe}^2 \gg 9\beta_{\rm th}^4 n_L^2$, we have $|\xi'| \approx c n_W[2\omega_2(\omega_2 - \Omega_e)^2/\omega_{pe}^2\Omega_e]$. Then, the damping (growth) rate is given by

$$\Gamma_\pm \approx \pm 2\pi^2 \frac{r_e c^2}{\omega} \frac{W_L}{\Delta n_L} \left(\frac{\omega_2}{\Omega_e}\right)^{1/2}, \tag{6}$$

where we assume $\omega_2 \le \Omega_e/2$. When we choose $n_L = 1$, the three-wave condition cannot be satisfied for $\Omega_e \to \omega_2$. Note that the damping (growth) rate (6) is different from that for whistler waves (cf. Eq. 5), while fixed-phase analysis predicts the two should be the same (e.g., Chian & Abalde 1999). Unlike the fixed-phase formalism in which the three interacting waves are monochromatic and their frequencies satisfy the three-wave conditions, in the random-phase formalism the relevant waves are broadband and so the frequency matching condition can be satisfied at different part of the frequency spreads. Thus, the damping (growth) rates for the three interacting waves are in general different.

## 3. Application to solar wind

Simultaneous observations of Langmuir waves and electromagnetic whistler waves have been made by the Ulysses spacecraft

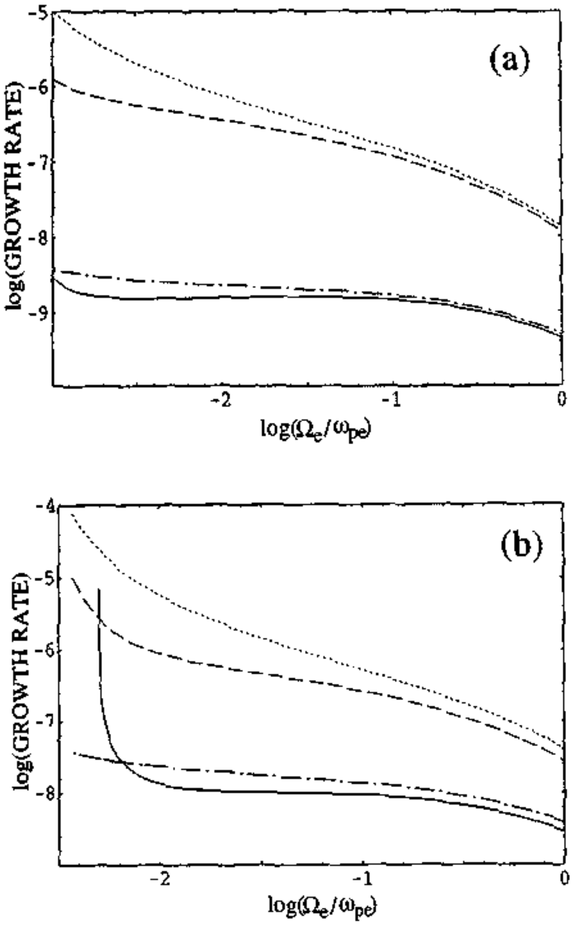


**Fig. 2a and b.** Growth rates, $\Gamma_W^{(-)}$ and $\Gamma_-$, as a function of $\Omega_e/\omega_{pe}$. **a:** $\omega_2/\omega_{pe} = 3.5 \times 10^{-4}$ and $n_L = 1$. **b:** $\omega_2/\omega_{pe} = 2.5 \times 10^{-3}$, $n_- = 5 \times 10^{-4}$ at $\Omega_e = 2\omega_2$. The solid, dot-dashed curves correspond respectively to the growth rate of forward-, back-propagating $W$-waves. The growth rates for the $l$-waves are plotted as dashed (forward-scattering) and dotted (back-scattering) curves.

in the solar wind (Kellogg et al. 1992; Lin et al. 1995; Stone et al. 1995). These interplanetary Langmuir-whistler events were detected in solar wind magnetic holes (Turner et al. 1977; Tsurutani et al. 1992; Winterhalter et al. 1994). In Sec. 2, we have formulated a three-wave theory for nonlinear coupling of Langmuir waves with whistler waves, valid for broadband plasma waves which are often seen in the solar wind. According to our theory, the nonlinear Langmuir-whistler interactions generate as a by-product circularly polarized radio waves near the solar wind plasma frequency.

From Sec. 2 we see that when $L$ is the pump, both whistler and $l$-waves can grow exponentially at rates $\Gamma_W^{(-)}$ and $\Gamma_-$, respectively, through $L \rightleftarrows l + W$. On the other hand, in the process $L + W \rightleftarrows r$, $r$-waves are in general damped at rate $\Gamma_+$ and can grow only through stimulated emissions ($S_+$). Assuming $dN_+/dt = 0$, one may find the maximum level of $r$-waves $N_+ \sim N_L N_W/(N_L + N_W)$, which shows that high level of $N_+$ can be achieved only when $N_W$ has reached a sufficiently high level.

Two different regimes of whistler growth in $L \rightleftarrows l + W$ can be identified, depending on the ratio $\omega_2/\Omega_e$ Consider first the case $\omega_2/\Omega_e \ll 1$. In this frequency regime, the three-wave matching conditions can be satisfied only for the triplet ($L$, $l$, $W$), but not for the triplet ($L$, $r$, $W$). As shown in Fig. 1a, the dispersion curves of $L$ and $l$ meet at the point $A$, i.e., the wave frequencies of $L$ and $l$ can be arbitrarily close to each other; whereas the wave frequencies of $r$ and $L$ differ at least by $\Omega_e/2$ (cf Fig. 1b). From $k = k_1 \pm k_2$, where +, − correspond respectively to the forward- and back-scattering, we have $n_L \approx n_- \pm n_W(\omega_2/\omega) \approx n_-$ as $n_W(\omega_2/\omega) \ll 1$. While Chian & Abalde (1999) discussed only the back-scattering case, we see both back- and forward-scattering involving $l$ are allowed in the limit $\omega_2 \ll \Omega_e$. Assuming $n_L \approx n_- \sim 1$, $\Delta n_L = n_L/2$ and using the typical solar wind parameters used by Chian & Abalde (1999), $\omega_2/2\pi = 5.6\,\mathrm{Hz}$, $\Omega_e/2\pi = 82\,\mathrm{Hz}$, $\omega_{pe}/2\pi = 16\,\mathrm{kHz}$, $\omega \sim \omega_{pe}$, $E_0 = 1\,\mathrm{mV\,m^{-1}}$, which gives the energy density ($m_e c^2$ per unit volume) $W_L = 5.4 \times 10^{-5}\,\mathrm{m^{-3}}$, we have $\Gamma_W^{(-)} \approx -2 \times 10^{-9}\,\mathrm{rad\,s^{-1}}$. The growth rate is much less than the fixed-phase growth rate obtained by Chian & Abalde (1999). This is expected since in general the random-phase processes are less efficient than the fixed-phase processes. In principle, one can boost the growth rate by increasing $W_L$. This is possible, for example, if microstructures in the distribution of electrons (similar to type III events) appear in interplanetary mangetic holes, which may enhance Langmuir wave amplitude to levels much higher than those observed (Melrose & Goldman 1987; Chian & Alves 1988). From Eq. (6), a higher growth rate can be obtained for $l$-waves. With the same solar wind parameters given above, we have $\Gamma_- \approx -1.5 \times 10^{-6}\,\mathrm{rad\,s^{-1}}$. The relevant growth rates as a function of $\Omega_e/\omega_{pe}$ for $\omega_2 \ll \Omega_e/2$ are shown in Fig. 2a. In this frequency regime, the growth rate for $l$-waves is significantly larger than that for whistler waves. In each case, back-scattering gives rise to higher growth rate than forward-scattering.

Consider next the frequency regime $\omega_2/\Omega_e \sim 1/2$ in which one of the two high-frequency waves has very small refraction index. In this case, the growth (damping) rate can increase significantly. For Fig. 1b, we have $n_L \ll 1$ (but $n_\pm$ cannot be small), which will not be considered further as we restrict our discussion only to the case of $n_L \sim 1$. For Fig. 1a, we have $n_+ \ll 1$ (while $n_L \sim 1$). Back-propagating whistler waves are damped at rate $\Gamma_W^{(+)}$ given by Eq. (5). For $\Delta n_L \sim n_L/2$, we estimate the damping rate $\Gamma_W^{(+)} \approx 2\pi^2 r_e c^2 (W_L/n_+)(\omega_2/\omega^2)$. However, for forward-propagating whistler waves, as shown in Fig. 1a, we can have $n_- \ll 1$ (with $n_L \sim 1$) for $\omega_2 \sim \Omega_e/2$. For smaller $\omega_2$, the resonance shifts towards even smaller $\Omega_e$. Forward-propagating waves grow exponentially at rate $\Gamma_W^{(-)} \approx -2\pi^2 r_e c^2 (W_L/n_-)(\omega_2/\omega^2)$ where $\omega_2 = \Omega_e/2$ is used, and from Eq. (6), the growth rate for $l$ waves is $\Gamma_- \approx -2\pi^2 (r_e c^2/\omega)(W_L/\Delta n_L)$. Plots of $-\Gamma_W^{(-)}$, $-\Gamma_-$ as a function of $\Omega_e/\omega_{pe}$ with a relatively higher $\omega_2$ are shown in Fig. 2b. As we choose $n_L = 1$, the three-wave condition cannot be satisfied for $\Omega_e \to \omega_2$, thus the plot range of $\Gamma_-$ and $\Gamma_W^{(-)}$ are restricted to $\Omega_e \geq 1.5\omega_2$. Fig. 2b shows that the growth rate for the $W$ waves can be comparable to and exceed that for the $l$ circularly polarized waves. In principle, we can have very large growth rate, $\Gamma_W^{(-)}$, by simply choosing smaller $n_-$ such that $|\xi'| \to 0$. Thus, it is possible that whistler waves with a frequency close $\Omega_e/2$ grow rapidly to the level at which the weak turbulence approximation is no longer valid (cf. Davidson 1972). Therefore, our random-phase result suggests a possibility of generating whistler waves with frequency close to $\Omega_e/2$.

When both waves grow to a level comparable to the Langmuir wave, i.e. $N_- \sim N_W \sim N_L$, the growth stops. Let the energy densities of whistler and $l$-waves be $W_W$ and $W_-$, respectively. The saturation levels for these two waves are estimated to be $W_W = (\omega_2/\omega)^2(n_W/n_L)W_L$, $W_- = (n_-/n_L)W_L$. Then, we have $W_W \approx (\omega_2/n_L\omega)(\omega_2/\Omega_e)^{1/2}W_L$ and hence, $W_W/W_L \ll 1$. For $\omega_2 = \Omega_e/2$, $\omega/2\pi \approx \omega_{pe}/2\pi = 16\,\mathrm{kHz}$, $n_L = 1$, we have $W_W/W_L = 4 \times 10^{-3}$ for $\omega_2/2\pi = 41\,\mathrm{Hz}$. The energy density of the $l$-waves can reach the level of the pump.

## 4. Conclusions

In the solar wind, whistler waves can grow exponentially as a result of three-wave interactions involving $L \rightleftarrows l + W$, provided that $N_L > N_-$. Whistler waves are damped exponentially through three-wave interaction involving $L + W \rightleftarrows r$. Growth of whistler waves favors forward-propagating with the frequency $\omega_2 \approx \Omega_e/2$. Thus, in the broadband approximation, for a given ambient mangetic field the $W$-waves produced most likely have a frequency near $\Omega_e/2$. The saturated energy density of whistler waves is at most a $\omega_2/n_L\omega_{pe}$ fraction of the energy density of the Langmuir pump waves. In general, the saturated energy density of $l$-waves can reach the level comparable to the pump. $l$-mode radio waves can grow exponentially, while $r$-waves are usually damped. Exceptionally, however, $r$-waves can be produced through stimulated emissions, with the maximum value given by $N_+ \sim N_L N_W/(N_L + N_W)$, when $W$-waves achieve a sufficiently high level of energy density through exponential growth (via $L \rightleftarrows l + W$). It follows that unless all relevant waves reach saturation so that $N_- \sim N_+$, in general $l$ waves are more likely observed than $r$-waves. The results of this paper show that in addition to Langmuir-ion acoustic turbulence (Chian & Alves 1988; Robinson, Cairns & Willes 1994; Abalde, Alves & Chian 1998) the solar wind seems to be rich in other types of nonlinear Langmuir phenomena such as Langmuir-whistler turbulence.

*Acknowledgements.* QL thanks ARC (Australia) for financial support through a fellowship. ACLC and FAB acknowledge the financial support from FAPESP (Brazil).

## References

Abalde, J. R., Alves, M. V., & Chian, A. C.-L., 1998, A&A, 331, L21.
Chian, A. C.-L., & Alves, M. V., 1988, ApJ, 330, L77.
Chian, A.C.-L., Lopes, S. R., & Alves, M. V., 1994, A&A, 290, L13.
Chian, A. C.-L., Abalde, J. R., Alves, M. V., & Lopes, S. R., 1997, Solar Phys., 173, 199.
Chian, A. C.-L., & Abalde, J. R. 1999, Solar Phys. 184, 403.
Davidson, R. C., 1972, Methods in Nonlinear Plasma Theory (New York: Academic Press).
Hasegawa, A., 1974, Phys. Rev. Lett., 32, 817.
Kellogg, P. T., Goetz, K., Lin, N., et al. 1992, Geophys. Res. Lett., 19, 1299.
Larsson, J. & Stenflo, L., 1973, Beitr. Plasma-phys., 13, 169.
Lin, N., Kellogg, P. J., MacDowall, R. J., et al. 1995, Geophys. Res. Lett., 22, 3417.
Luo, Q., & Melrose, D. B., 1995, ApJ, 452, 346.
Luo, Q., & Melrose, D. B., 1997, J. Plasma Phys., 58, 345.
Luo, Q., & Chian, A. C.-L., 1997, MNRAS, 289, 52.
Melrose, D. B., 1986a, Instabilities in Space and Laboratory Plasmas (Cambridge: Cambridge University Press).
Melrose, D. B., 1986b, J. Plasma Phys., 36, 269.
Melrose, D. B., & Goldman, M. V., 1987, Solar Phys., 107, 329.
Novikov, A. A., Rabinovich, M. I., & Fainstein, S. M., 1976, Sov. Phys. Tech. Phys., 20, 829.
Robinson, P. A., Cairns, I. H., & Willes, A. J., 1994, ApJ, 422, 870.
Shukla, P. K. & Sharma, R. P., 1982, Phys. Rev., A25, 2816.
Stenflo, L., 1970, J. Plasma Phys., 4, 585.
Stenflo, L., & Shukla, P. K., 1995, J. Geophys. Res. 100, 17261.
Stone, R. G. et al., 1995, Science, 268, 1026.
Tsurutani, B. T., Southwood, J., Smith, E. J., & Balogh, A., 1992, Geophys. Res. Lett., 19, 1267.
Turner, J. M., Burlaga, L. F., Ness, N. F., & Lemaire, J. F., 1977, J. Geophys. Res., 82, 1921.
Tsytovich, V. V., 1972, An Introduction to the Theory of Plasma Turbulence (Oxford: Pergamon Press).
Winterhalter, D., Neugebauer, M., Goldstein, B. E., et al. 1994, J. Geophys. Res., 99, 23371.