INTERNATIONAL ATOMIC ENERGY AGENCY
UNITED NATIONS EDUCATIONAL, SCIENTIFIC AND CULTURAL ORGANIZATION
INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS
I.C.T.P., P.O. BOX 586, 34100 TRIESTE, ITALY, CABLE: CENTRATOM TRIESTE

H4-SMR 393/35

SPRING COLLEGE ON PLASMA PHYSICS

15 May - 9 June 1989

PLASMA PHYSICS VIA SOLAR RADIOASTRONOMY

M. Messerotti

Solar Astrophysics Group
Astronomical Observatory
Via G. B. Tiepolo 11
I - 34131 Trieste

PLASMA PHYSICS VIA SOLAR RADIOASTRONOMY

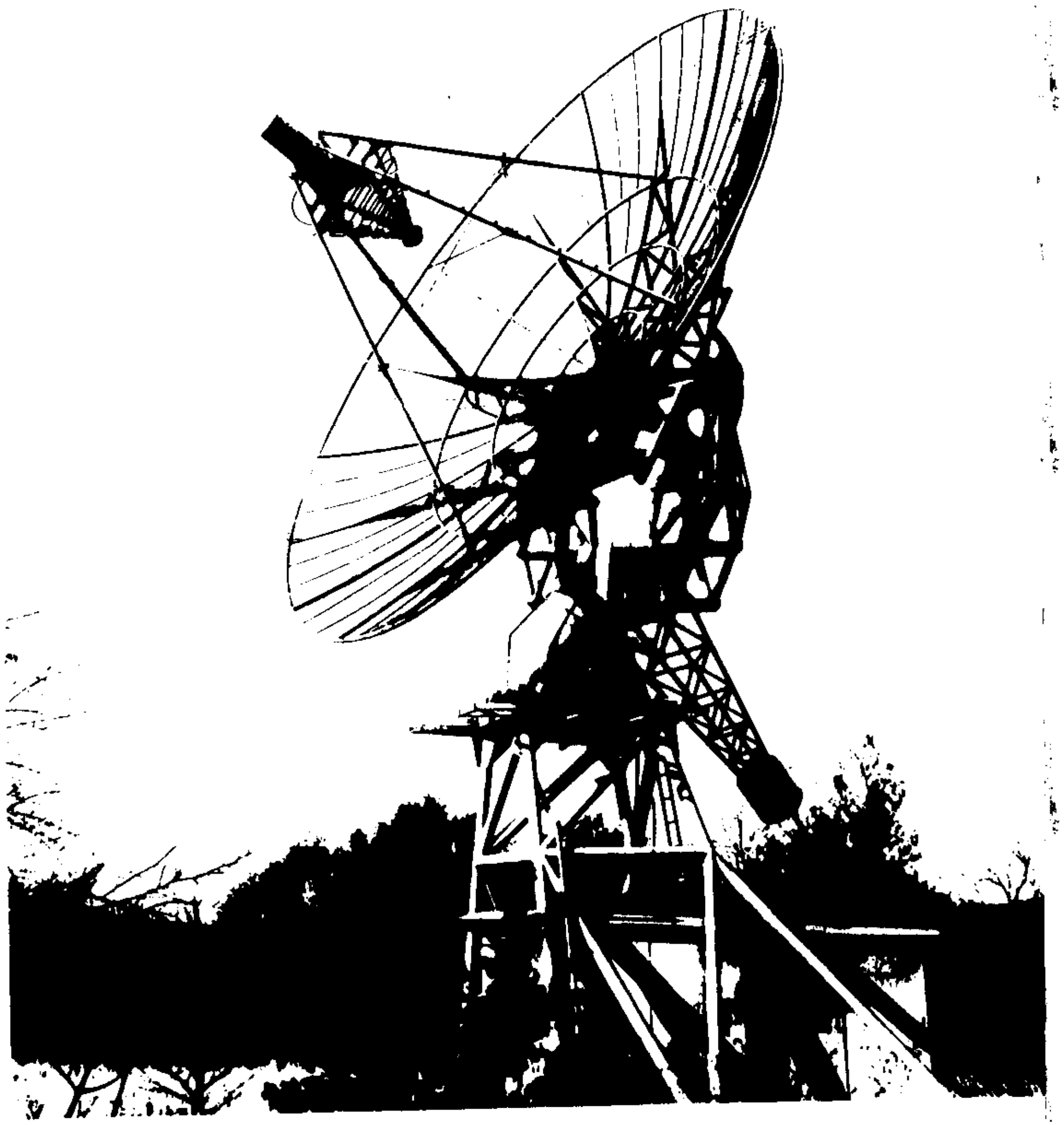
M. MESSEROTTI *

* Permanent address:

Solar Astrophysics Group
Astronomical Observatory
Via G.B. Tiepolo 11
I-34131 TRIESTE
ITALY

SPRING COLLEGE ON PLASMA PHYSICS
May 15 - June 9 1989

The 10m parabolic antenna of the solar multi-channel radiopolarimeter (200-800 MHz, LCP-RCP) operated by the Trieste Astronomical Observatory



SOLAR RADIOASTRONOMY

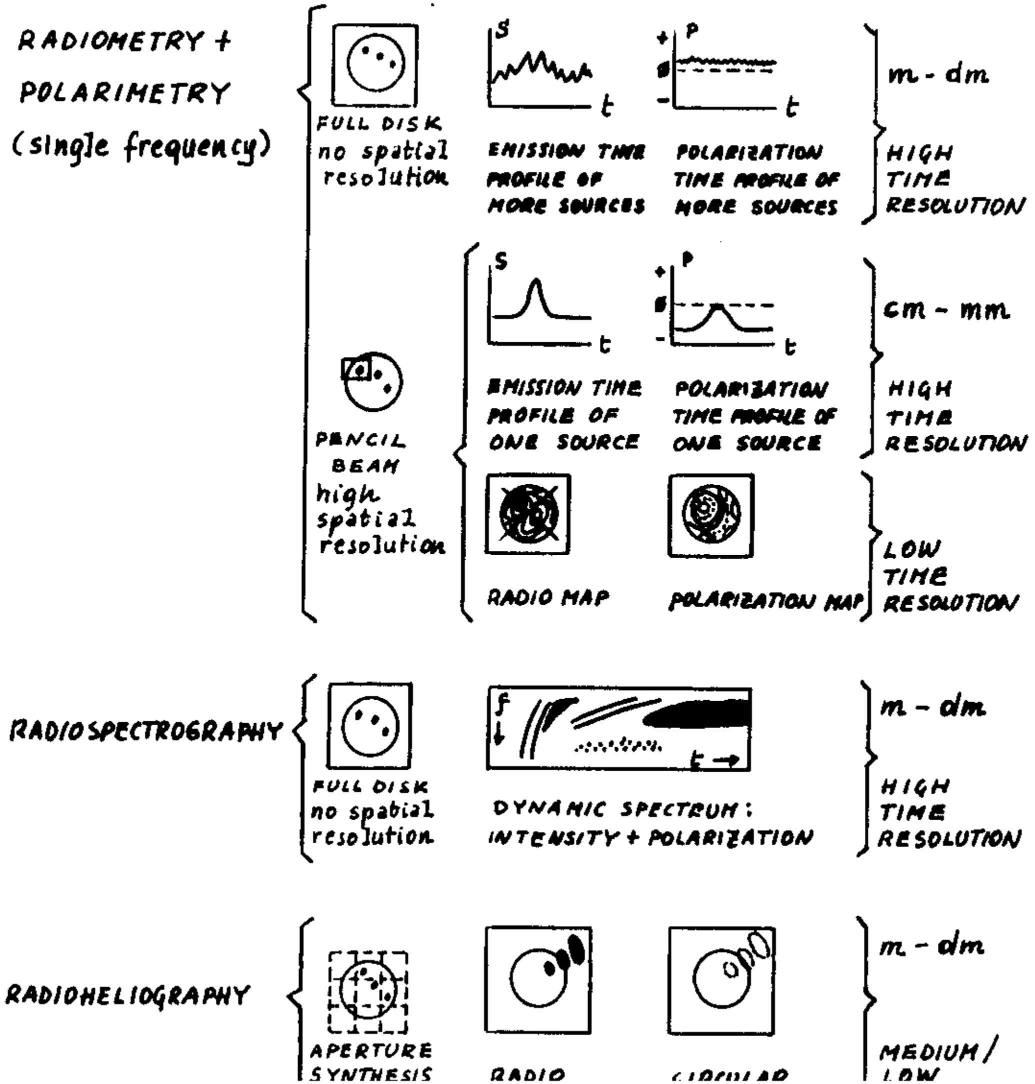
- 1942 - S. Hey identifies the radio emission from the Sun
- 1950 - Wild and McCready classify solar radio events according to their dynamic spectra

Observational Techniques in Solar Radioastronomy

Observable PARAMETERS:

1. S [$W/Hz \cdot m^2$] RADIO FLUX DENSITY
2. $P = (S_L - S_R)/(S_L + S_R)$ CIRCULAR POLARIZATION
3. L SOURCE SIZE

Instrumental CONFIGURATIONS:



Interpretation of a DYNAMIC SPECTRUM

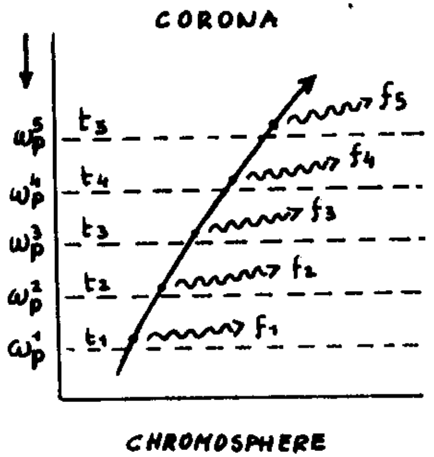
Assume emission of em radiation at $\omega \gtrsim \omega_p$ with ω_p - LOCAL PLASMA FREQUENCY.

$$\omega_p = f(n_e) \;,\quad n_e = f(r) \Rightarrow \omega_p = f(r)$$

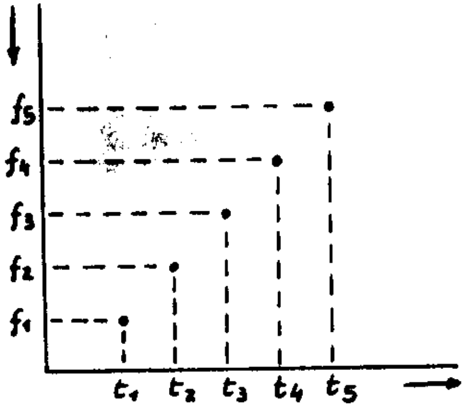
with n_e - electron density, r - radial distance from the Sun.

E.g.: CHROMOSPHERE $n_e = 10^{17}\, m^{-3}$ $\omega_p = 2.85$ GHz

CORONA $n_e = 10^{15}\, m^{-3}$ $\omega_p = 285$ MHz

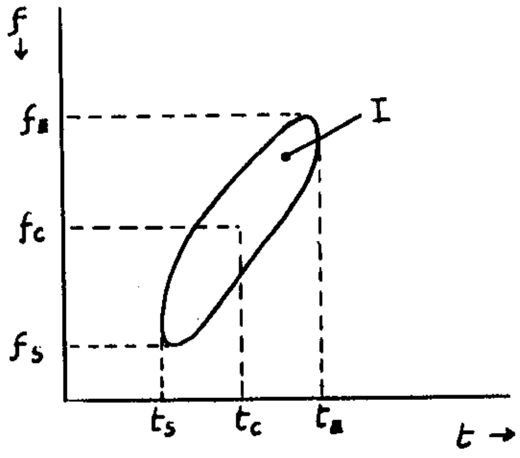


SUN



RADIO SPECTRUM

DYNAMIC SPECTRUM PARAMETERS



f_S - STARTING FREQUENCY

f_E - ENDING FREQUENCY

$f_C = (f_S - f_E)/2$ - CENTRAL FREQUENCY

t_S - STARTING TIME

t_E - ENDING TIME

$t_C = (t_E - t_S)/2$ - CENTRAL TIME

$|t_S - t_E|$ - event duration

$|f_S - f_E|$ - event bandwidth

I - event intensity

SYNOPSIS of Solar Radio Emission

QUIET SUN → quiet Sun radio emission :

- bremsstrahlung of thermal electrons (P ~ Ø) + cyclotron emission (P → (x)) ;
- T_b = 6500 K (λ = 2 mm) ÷ 10^6 K (λ = 20 cm)

PERTURBED SUN → A) Slowly varying component (S)

- λ 3 ÷ 60 cm ; • close association with sunspot groups (10.7 cm ↔ R); • chromospheric or coronal source
- bremsstrahlung (P ~ Ø) + cyclotron emission (P → (x)).

B) Fast varying component :

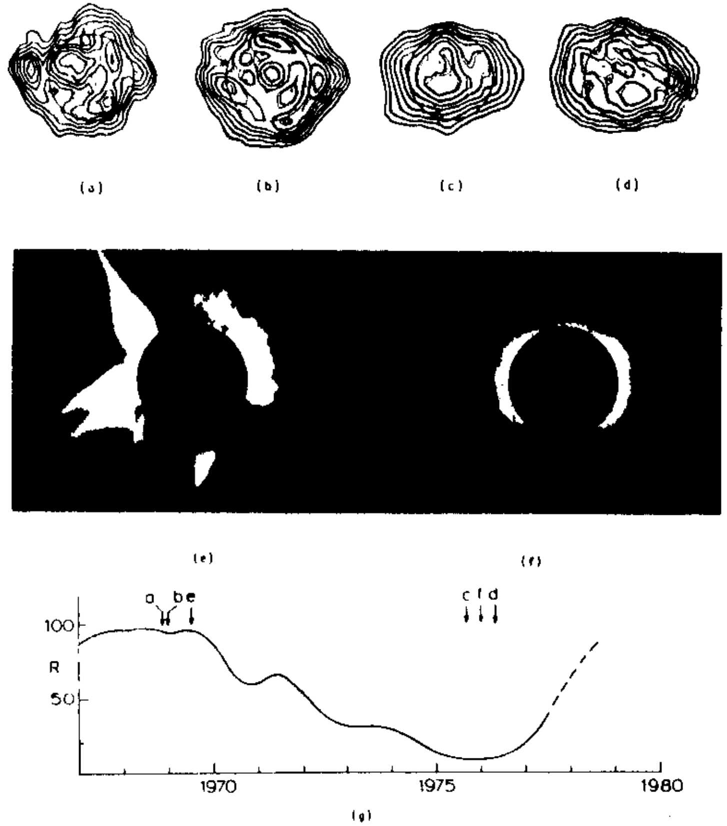
1. TYPE I BURSTS (NOISE STORMS)
2. TYPE II BURSTS (low frequency drift)
3. TYPE III BURSTS (high frequency drift)
4. TYPE IV BURSTS (broadband continuum)
5. TYPE V BURSTS (metre continuum)

- These events occur according to a TIMING closely related to the time evolution of the associated FLARE (exception : type I bursts) :

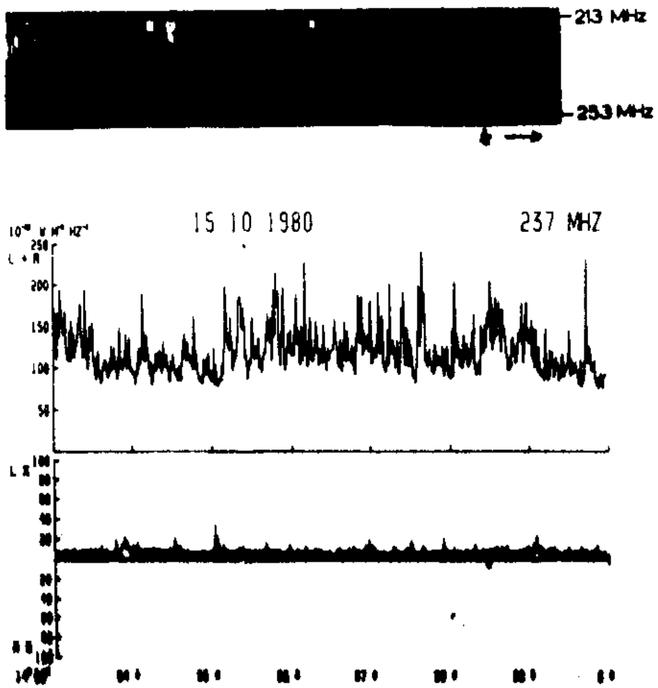
1) type III (+ type V) → IMPULSIVE PHASE

2) type II (+ type IV) → GRADUAL PHASE

80 MHz radio maps of the quiet Sun (Culgoora radio obs.) for different periods of the solar cycle [McLean & Labrum , 1985] p. 457



NOISE STORM: continuum + TYPE I BURSTS

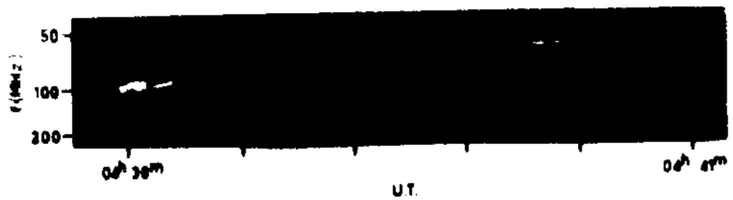


Utrecht Radio Observatory

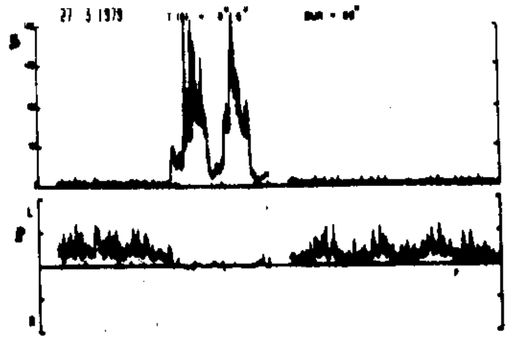
Trieste Solar Group

	Type I Bursts	Continuum
Duration at 100 MHz	≲ 1 s	days or weeks
T_b	≳ 10^{10} K	≳ 10^{9} K
Circular Polarization	50 ÷ 100% (0)	same as bursts
Occurring frequ. range	50 ÷ 300 MHz	" " "
Bandwidth	≈ 1 MHz	≈ 100 MHz
Source height	0.1 ÷ 0.6 $R_\odot$	same as bursts
Magnetic topology	closed	" " "
Associated phenomena	big sunspots	" " "
Emission mechanism	plasma (F)	" " "
Source size	~ 1'.5	1' (40B) –

TYPE II BURSTS

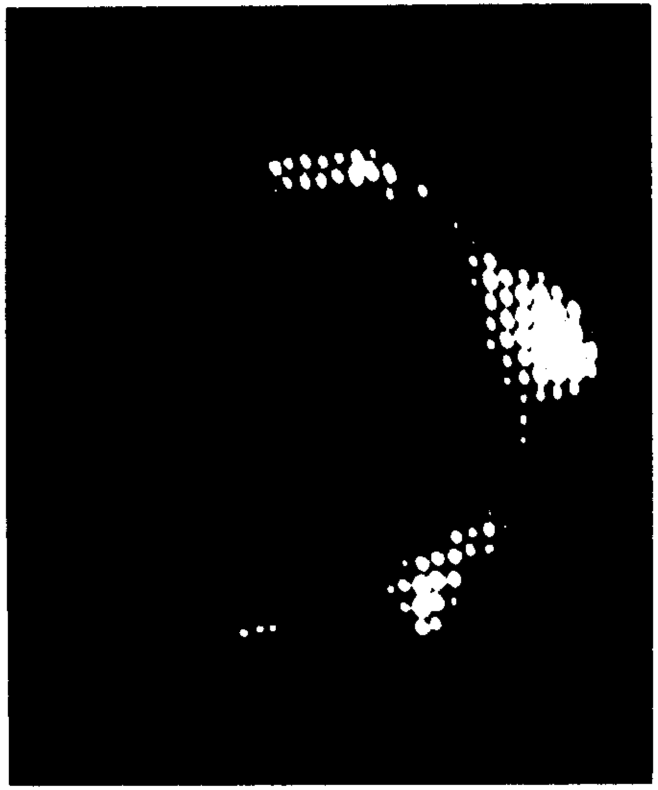


October 9, 1969 (Dulk, 1970 in Krüger 1979, p. 104)



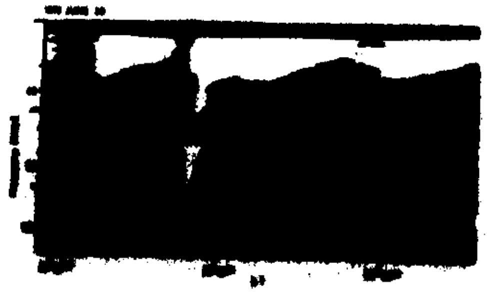
Trieste Solar Group

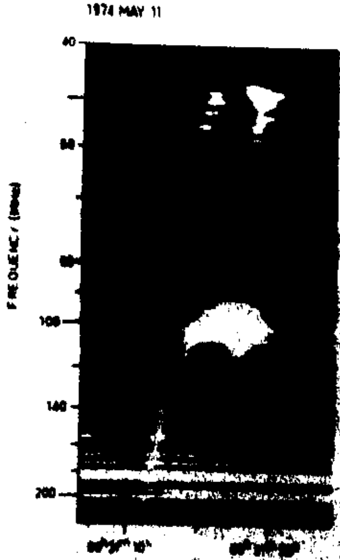
Duration at 100 MHz	≳ 10 min
T_b	10^{8} - 10^{11} K
Circular Polarization	~ 0%
Occurring frequ. range	200 - 1 MHz
Bandwidth	10 MHz
Source height	0.2 - 200 $R_\odot$
Magnetic topology	open
Associated phenomena	flare, shock wave
Emission mechanism	plasma (F+H)

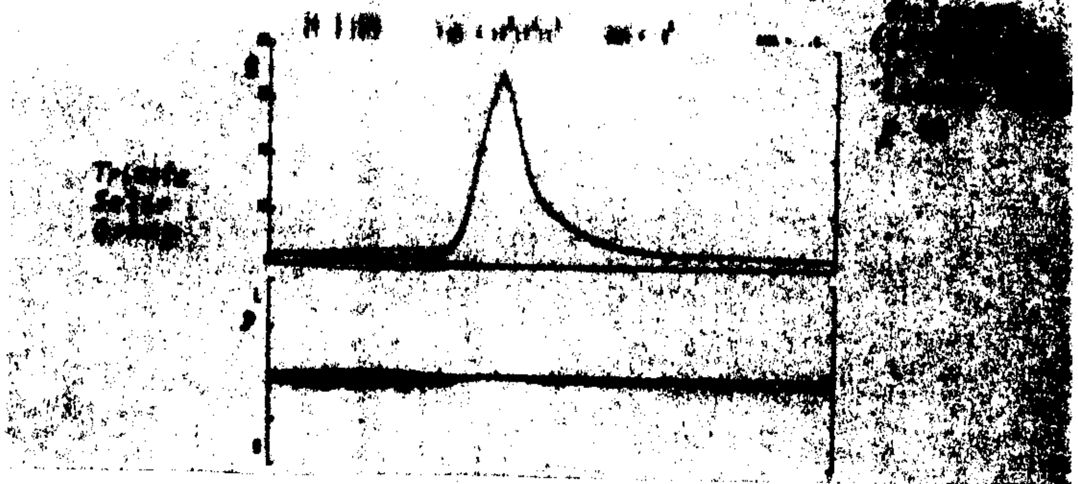


Culgoora radioheliograph, March 30, 1969 :
type II burst sources + continuum source
(Smerd, 1970 in Krüger 1979, p. 106)

TYPE III BURST
TYPE V BURST



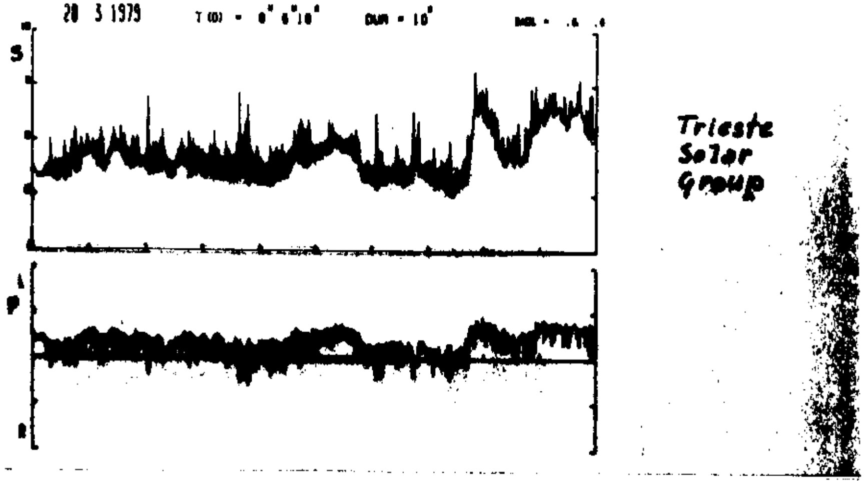




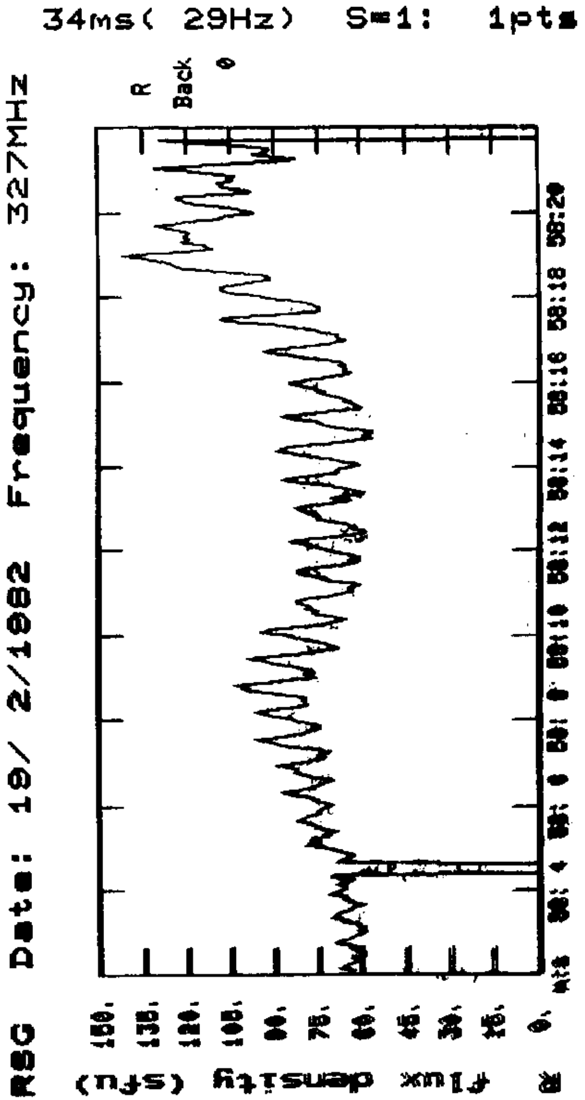
	Type III	Type V
Duration at 100 MHz	a few seconds	> 1 min
T_b	$10^{8} - 10^{12}$ K	$10^{8} - 10^{11}$ K
Circular Polarization	F → 30%, H → 10% (o)	< 10% (x)
Occurring Frequency Range	200 - 1 MHz	100 - 10 MHz
Bandwidth	10 MHz	50 MHz
Source height	0.2 - 200 $R_\odot$	0.5 - 2 $R_\odot$
Magnetic topology	open (closed)	open ?
Associated phenomena	electron beam c/3	follow some type III
Emission mechanism	plasma (F+H)	plasma (H)

TYPE IV BURSTS

Utrecht Radio Observatory



Trieste Solar Group

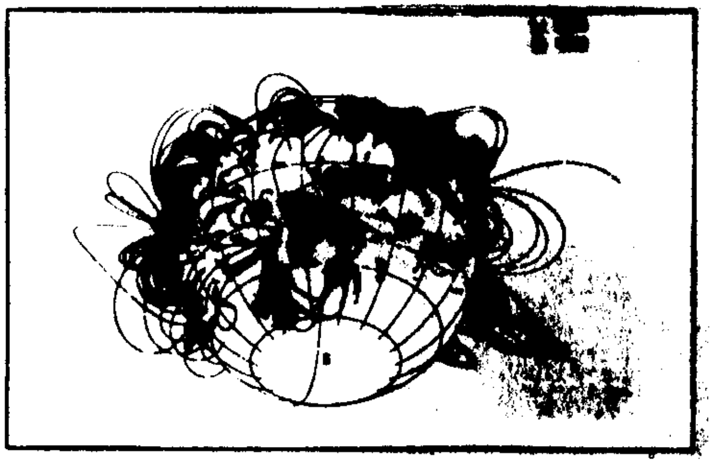


Radio pulsations during a type IV burst (Trieste Solar Group)

Duration at 100 MHz	a few hours
T_b	$> 10^9$ K
Circular Polarization	60 ÷ 100% (o)
Occurring frequ. range	50 ÷ 300 MHz
Bandwidth	100 MHz
Source height	0.1 ÷ 0.6 $R_\odot$
Magnetic topology	closed ?
Associated phenomena	flare, late phase
Emission mechanism	plasma (F)

THE SOLAR CORONA

WHITE LIGHT CORONA (eclipse: June 30, 1973; G.A. NewKirk, HAO)



CORONAL MAGNETIC FIELD extrapolated in a current-free approximation (Ambroš, 1973)

- MAGNETIC FIELDS
- CURRENTS = free

ENERGETIC PHENOMENA

FLUID MOTION

↓

CHANGE IN THE MAGNETIC FIELD TOPOLOGY

↓

RECONNECTION

↓

MAGNETIC ENERGY RELEASE (10^{32} erg)

⇛

SOLAR FLARES

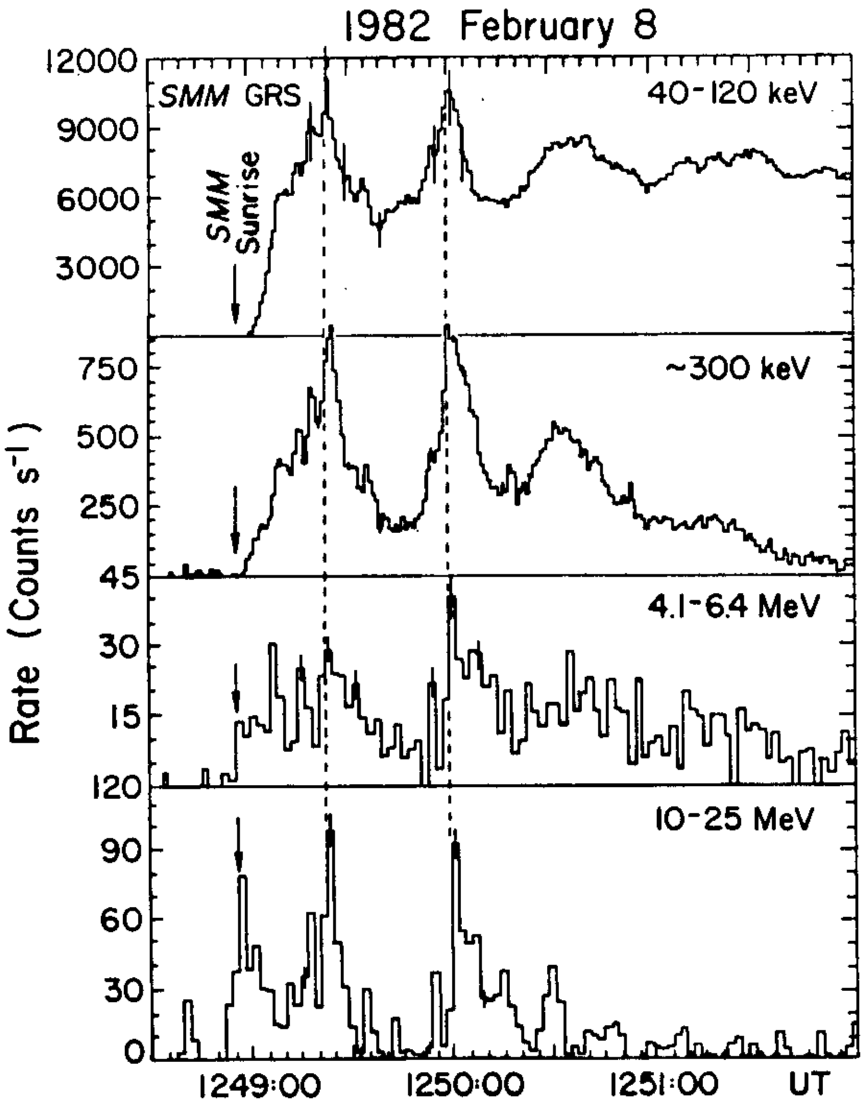
→ PARTICLE ACCELERATION (10^9 K)

→ HEATING (10^7 K)

- e (10-100 keV) ⇒ HXR, type III, IPM
- p (10 MeV) ⇒ γ-ray LINES, IPM
- RELATIVISTIC e ⇒ γ-ray CONTINUUM, type III, IPM

(almost contemporaneously)!

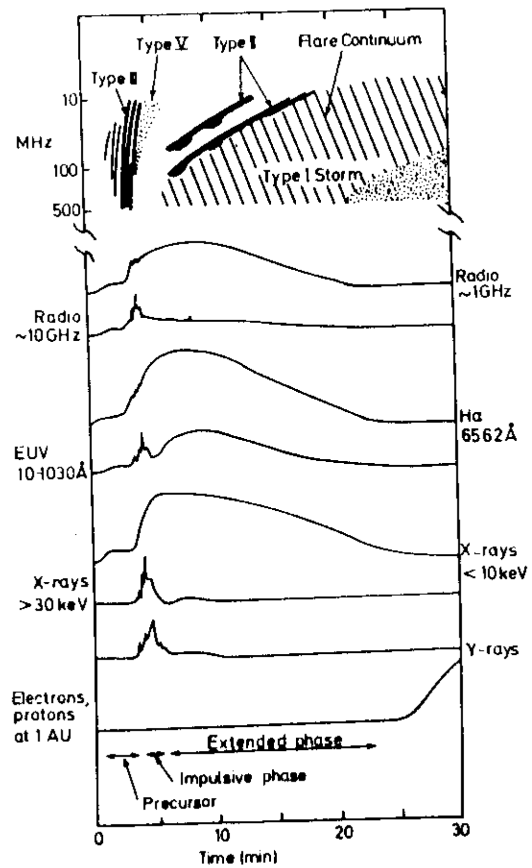
[Mechanisms: - STOCHASTIC ACCELERATION
- DIRECT ELECTRIC FIELD
- SHOCK]



SMM - GRS data (from Chupp et al., 1985)

1^{st}, 2^{nd}, 4^{th} panel → BREMSSTRAHLUNG OF ELECTRONS

3^{rd} panel → SUM OVER SPECTRAL LINES ORIGINATING FROM PROTONS



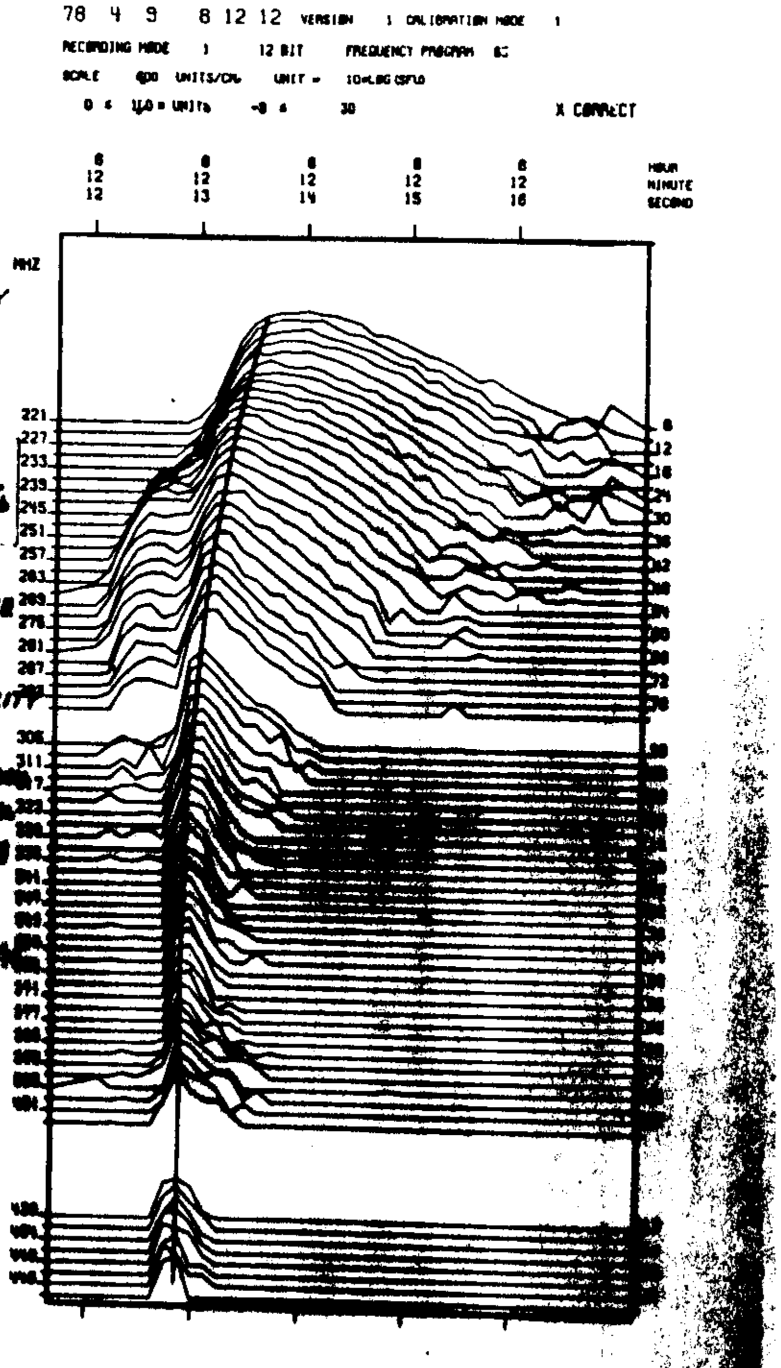
Timing of a solar flare in different bands of the electromagnetic spectrum (Kane, 1974 in McLean & Labrum 1985 p. 55)

THE SOLAR CORONA AS A PROPAGATING MEDIUM

BEAM VELOCITY and DRIFT RATE

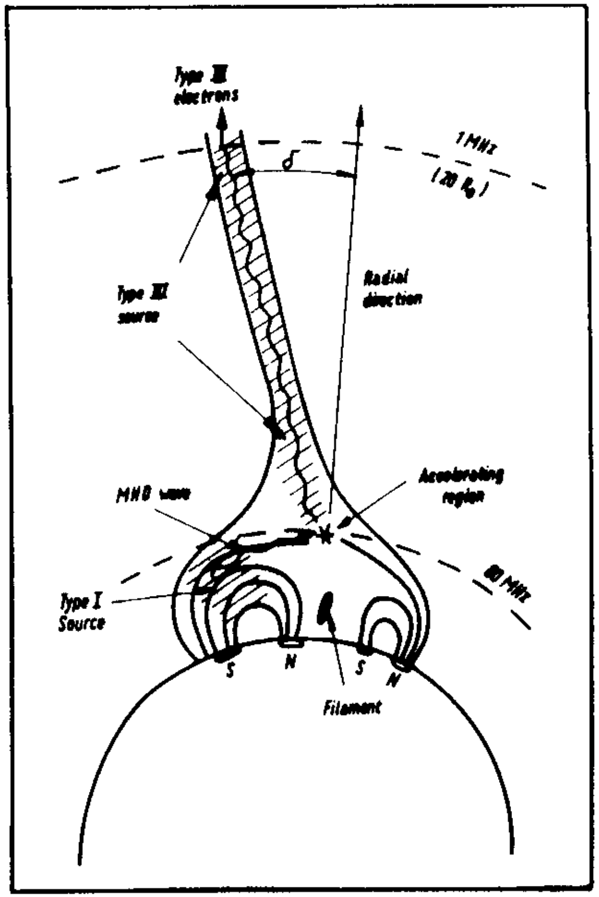
$$\frac{d\nu}{dt} = -\frac{\nu \cos\vartheta}{2\lambda} v_b$$

- $\frac{d\nu}{dt}$ – DRIFT RATE
- v_b – BEAM VELOCITY
- ϑ – angle between beam motion and density gradient
- λ – density [illegible] height



RADIOSPECTROGRAM of a TYPE III EVENT

(Ikarus Spectrometer, ETH, Zürich)



(Stewart and Labrum, 1972)

(see Krüger 1979, p. 139)

RADIOEMISSION BY BEAMS OF PARTICLES

(ELECTRONS → TYPE III)

THE THEORY MUST ACCOUNT FOR:

(1) BEAM FORMATION (bump formation)

(2) BEAM EVOLUTION (quasi-linear relaxation)

(3) BEAM-PLASMA INSTABILITY (bump-on-tail instability)

(4) PLASMA – EM WAVE CONVERSION (many theories proposed)

MAIN DIFFICULTIES IN INTERPRETATION:

(A) STURROCK'S DILEMMA in point (2);

(B) LOW EFFICIENCY in point (4).

(PROTONS → LOW-DRIFT TYPE III)

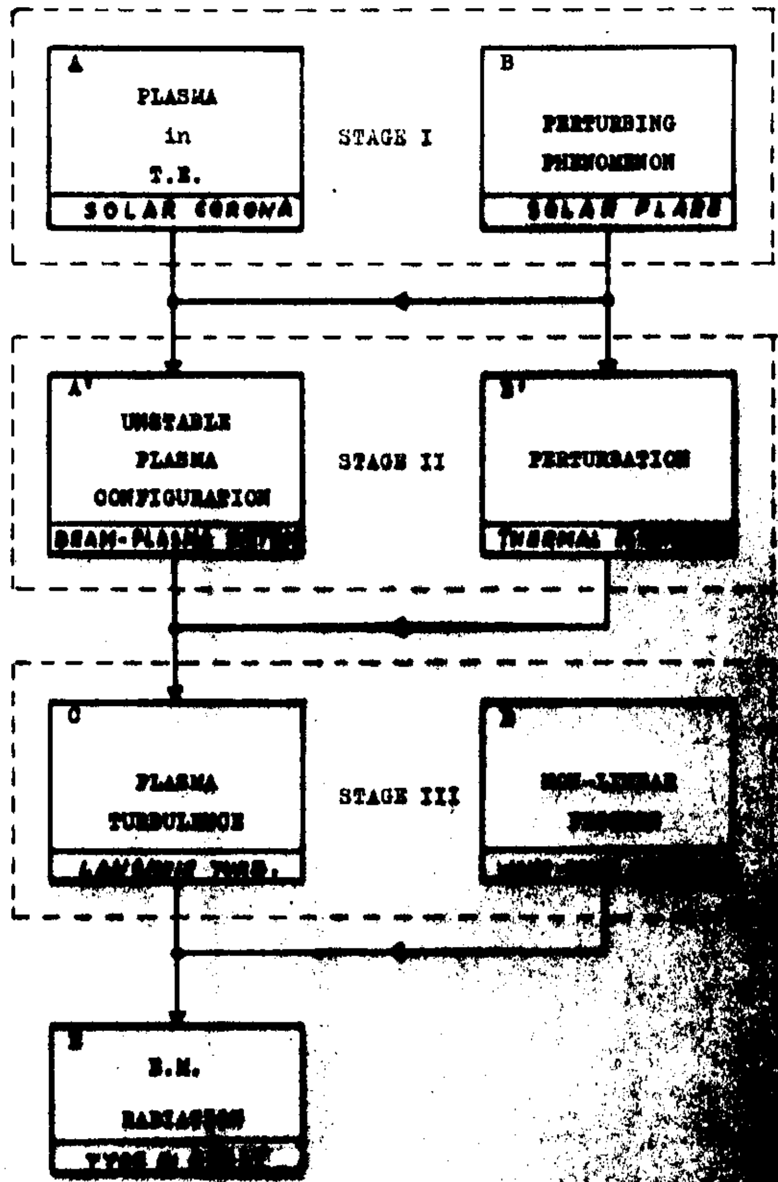
— RESEARCH PROJECT —

feedback

a. THEORETICAL APPROACH TO POINTS (1)..(4) by using the methods of plasma physics

b. DETAILED ANALYSIS OF EXISTING RADIO OBSERVATIONS

THE PLASMA RADIATION MECHANISM FOR THE TYPE III BURST



RADIO EMISSION → information about the perturbation and the medium through which it propagates:

OBSERVED PARAMETERS	INFERENCES
1. Observation Frequency	density, M.F. (ω_p/Ω_e)
2. Radiation Intensity	saturation mechanism, perturbation
3. Duration, Rise and Decay Time, Periodicity	temporal dependence of plasma processes
4. Polarization	Magnetic Field
5. Frequency Drift	propagation velocity of the exciting agent
6. Observed source size	real source size

EVIDENCE of ACCELERATED PROTONS IN THE SOLAR ATMOSPHERE

- PROTONS are ACCELERATED during FLARES as well as electrons and it has been proposed (Simnett, 1985) that protons in the energy range $10^2 \div 10^3$ MeV are the dominant ENERGY CARRIERS during the impulsive phase.

OBSERVATIONS of their existence:

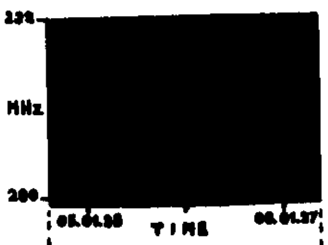
A). DIRECT, FAR FROM THE FLARING SITE

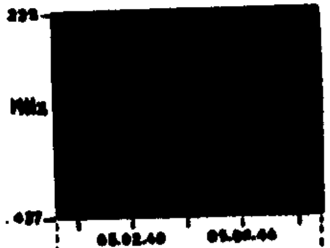
- INTERPLANETARY PROTONS from
  - COSMIC RAY FLARES, [illegible], Ground Level Effects
  - PROTON FLARES, [illegible]
  - (– [illegible])

B) INDIRECT, NEAR THE FLARING SITE

[illegible]

RADIO SIGNATURE of PROTON BEAMS





10 July 1980,
ETH, IKARUS
SPECTROMETER

SLOW DRIFT	TYPE III	
20 MHz/s	150 MHz/s	DRIFT RATE
13.000 Km/s	100.000 Km/s	BEAM VELOCITY
0.6 s (electrons) 5.0 m (protons)	30 s (electrons)	COLLIS. TIME

[After Benz & Simnett, Nature, 320, 508 (1986)]

REMARKABLE POINTS:

for the SLOW DRIFT BURST

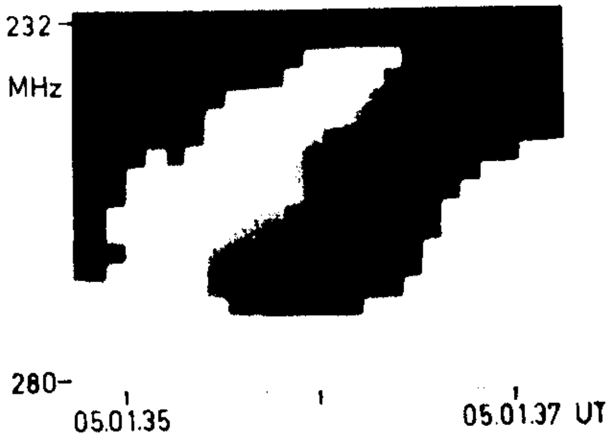
(i) the DRIFT RATE is 1 order of magnitude smaller than that of a regular type III;

(ii) the BEAM VELOCITY $\approx 1 \div 2\ v_{T_e}$ $(2 \cdot 10^6\ K)$ ⇒ the two-stream instability is Landau damped

(iii) the COLLISION TIME for ELECTRONS is too short (≪ DURATION) ⇒ an electron beam would not propagate

↓

THE EXCITERS can be PROTON BEAMS with PROTON ENERGIES 0.56 ÷ 3.7 MeV



(a)

SLOW-DRIFT TYPE III BURST

(b)

TYPE III BURST

(Ikarus spectrometer, ETH, Zürich)

PROTON BEAMS in CORONAL PLASMA

OAL: The verification of the proton beam in coronal conditions as a possible candidate for the interpretation of solar radio bursts.

ISKS:

LINEAR REGIME of an UNSTABLE BEAM-PLASMA SYSTEM (Messerotti, 1987): analytical and numerical approach for the cold and warm case; whole interval of proton beam velocities.

NON-LINEAR REGIME:

a) monoenergetic proton beam in cold background plasma: theoretical estimation, numerical calculations using a particle numerical code.
   - Comparison of growth rates, saturation levels and trapping periods for electron and "proton" beams (for various m_b/m_e).
   - Possible improvement ⇒ better description of beam-plasma system (e.g. $L = 2\pi \rightsquigarrow L = 20\pi$).

   ∴ The level of saturation is a parameter of fundamental importance for solar radioastronomy because it is connected with the intensity of the observed radio bursts through the transformation.

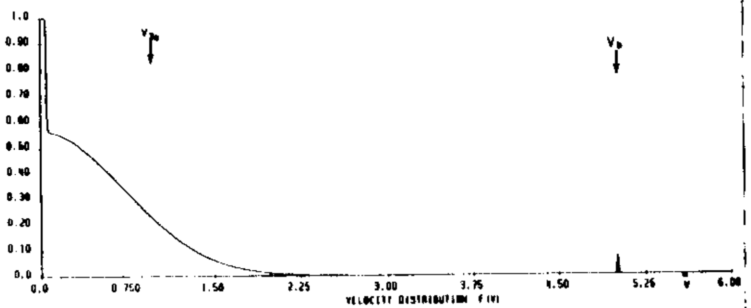
b) cold proton beam in warm background plasma for various proton beam velocities;

c) Warm proton beam in warm background plasma for various proton beam velocities (bump-on-tail instability, ion-acoustic instability);

d) Proton beam propagating perpendicular to magnetic field.

3. QUASI-LINEAR APPROACH for long time evolution of proton beam

   a) Proton beam in inhomogeneous corona $n_e = n_e(r)$: quasi-linear approach, propagation effects.



A typical beam-plasma system represented by a gap distribution

BEAM-PLASMA INSTABILITY

The cold case in the electrostatic approximation

<u>The electrostatic dispersion relation in the cold case</u>

In the frame of the linear theory (← small perturbation amplitudes) the electrostatic approximation ($\bar{\nabla} \times \bar{E} = 0$) can be applied to derive the dispersion relation for a COLLISIONLESS BEAM-PLASMA SYSTEM consisting of a particle beam streaming in an unmagnetized background plasma (IONS + ELECTRONS).

Electrostatic longitudinal oscillations are considered as solutions in the form of traveling plane waves and a 1-D problem can be studied to make the notation simple.

In the limit of vanishing temperatures ($T_j \to 0$) the 3 unperturbed plasma components are represented by δ-functions in the velocity space:

$$f_{oe}(v) = n_o\,\delta(v) \qquad f_{oi}(v) = n_o\,\delta(v) \qquad f_{ob}(v) = n_b\,\delta(v - V_b)$$

BACKGROUND ELECTRONS & IONS — BEAM

$v = v_x$ VELOCITY

n_o UNPERTURBED PLASMA NUMBER DENSITY

$n_b = \varepsilon\, n_o$ BEAM " "

[$\varepsilon \ll 1 \Rightarrow$ weak beam]

$V_b = V_{bx}$ STREAMING VELOCITY of the BEAM.

- The propagation is supposed to occur along the x-axis.
- The charge neutrality is assumed as $n_e = n_i = n_o$ with a neglegible perturbation caused by the beam ($n_b \ll n_o$).

The ELECTROSTATIC DISPERSION RELATION reads (see e.g. Mikhailovskii, 1974):

$$D(\omega, k) = 1 - \frac{\omega_{pe}^2}{\omega^2} - \frac{\omega_{pi}^2}{\omega^2} - \frac{\omega_{pb}^2}{(kV_b - \omega)^2} = 0$$

$\omega = \omega_r + i\gamma$ COMPLEX FREQUENCY

$\omega \in \mathbb{C}$ $\begin{cases} \omega_r \in \mathbb{R} & \text{(REAL FREQUENCY)} \\ \gamma \in \mathbb{R} & \text{(LINEAR GROWTH RATE)} \end{cases}$

$k \in \mathbb{R}$ REAL WAVENUMBER

$\omega_{pe} = \left[\frac{4\pi n_o e^2}{m}\right]^{1/2}$ BACKGROUND ELECTRONS PLASMA FREQU.
e, m electron charge and mass

$\omega_{pi} = \left[\frac{4\pi n_o e^2}{M}\right]^{1/2} = \left(\frac{m}{M}\right)^{1/2} \omega_{pe}$ BACKGROUND IONS PLASMA FREQU.
M proton mass (mainly protons)

$\omega_{pb} = \left[\frac{4\pi n_b e^2}{M}\right]^{1/2} = \varepsilon^{1/2} \left(\frac{m}{m_b}\right)^{1/2} \omega_{pe}$ BEAM PARTICLE PLASMA FREQU.
m_b beam particle mass

The dispersion relation can be rewritten as:

$$D(\omega, k) = 1 - \frac{\omega_{pe}^2}{\omega^2} - \frac{1}{MRP} \frac{\omega_{pe}^2}{\omega^2} - \frac{\varepsilon}{MRB} \frac{\omega_{pe}^2}{(\omega - kV_b)^2} = 0$$

$MRP = M/m \simeq 1836$ PROTON TO ELECTRON MASS RATIO

$MRB = m_b/m$ BEAM PARTICLE TO ELECTRON MASS RATIO

That is a 4th order algebraic equation in ω and its SOLUTIONS $\omega_i = \omega_i(k)$ $(i = 1..4)$ are the PERMITTED MODES in the beam-plasma system.

If ω_{ri} has a non-vanishing imaginary part γ_i, the waves are damped ($\gamma_i < 0$) or growing ($\gamma_i > 0$).

∴ THE POSSIBLE GROWING MODES ARE OF INTEREST TO STATE IF THE PLASMA RADIATION MECHANISM CAN WORK EFFECTIVELY.

Numerical solutions of the dispersion relation

After some variable substitutions as:

$$\tilde{\omega} = \omega/\omega_{pe} \qquad \tilde{k} = kV_b/\omega_{pe}$$

the DISPERSION RELATION becomes:

$$\tilde{D}(\tilde{\omega}, \tilde{k}) = 1 - \frac{1}{\tilde{\omega}^2} - \frac{1}{MRP}\frac{1}{\tilde{\omega}^2} - \frac{\varepsilon}{MRB}\frac{1}{(\tilde{\omega} - \tilde{k})^2} = 0$$

which is suitable to be solved numerically.
It is a 4th order algebraic equation of normalized complex variable $\tilde{\omega} = \tilde{\omega}_r + i\tilde{\gamma}$ and real coefficients, which depends only on the FREE PARAMETER ε related to the beam density

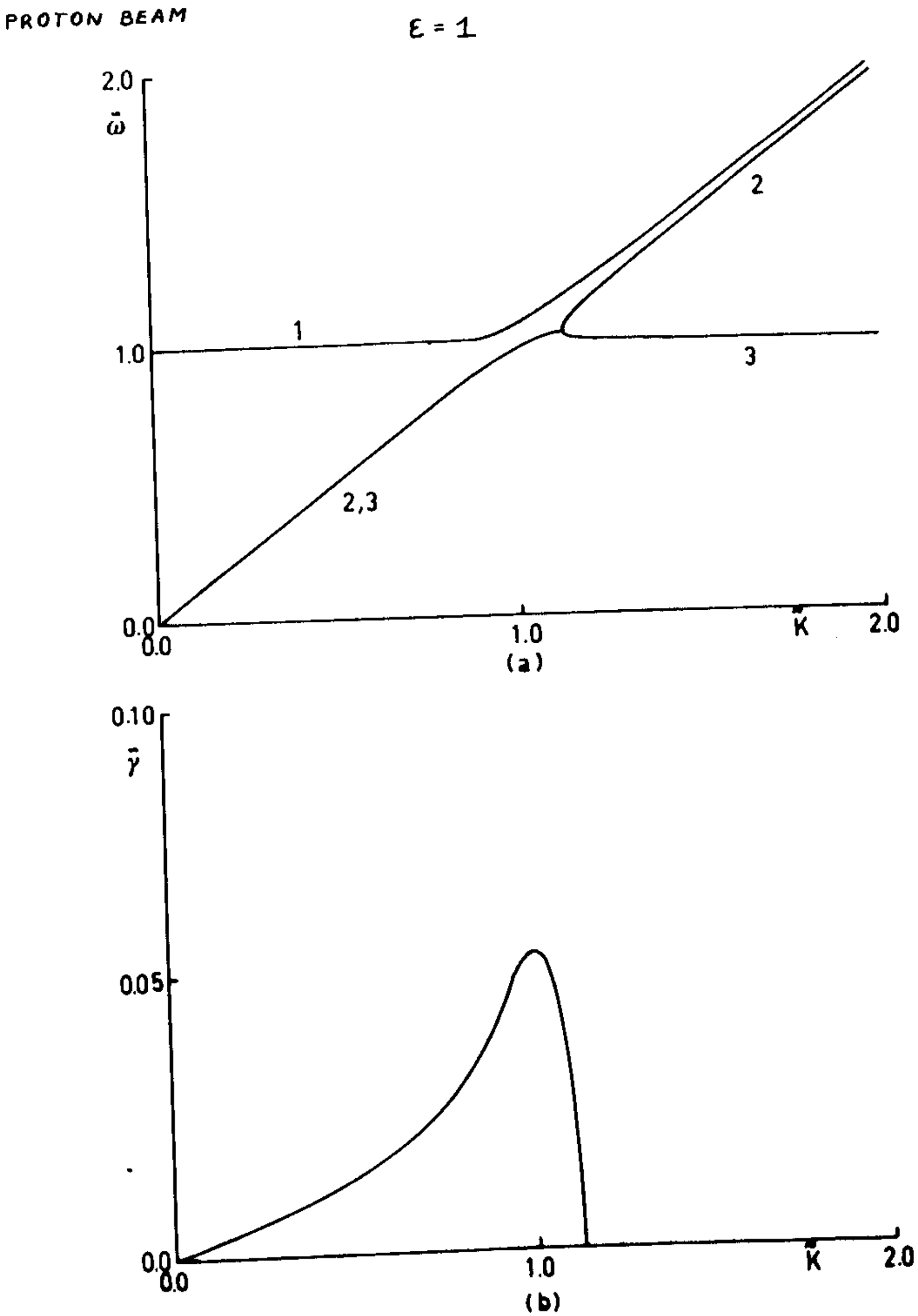
The REAL PARTS of the solutions $\tilde{\omega}_{ri} = \tilde{\omega}_{ri}(\tilde{K})$ $(i = 1..4)$ are the branches of the dispersion relation and the IMAGINARY PARTS $\tilde{\gamma}_i = \tilde{\gamma}_i(\tilde{K})$ are the corresponding GROWTH RATES.
If MRB = MP a PROTON BEAM is considered, whereas MRB = 1 represents an ELECTRON BEAM.

Numerical results

Three cases of beam density were considered for protons and electrons respectively: 1. $\varepsilon = 1$, STRONG BEAM; 2. $\varepsilon = 10^{-2}$ and 3. $\varepsilon = 10^{-6}$, WEAK BEAM (extreme values estimated for electron beams producing type III bursts.

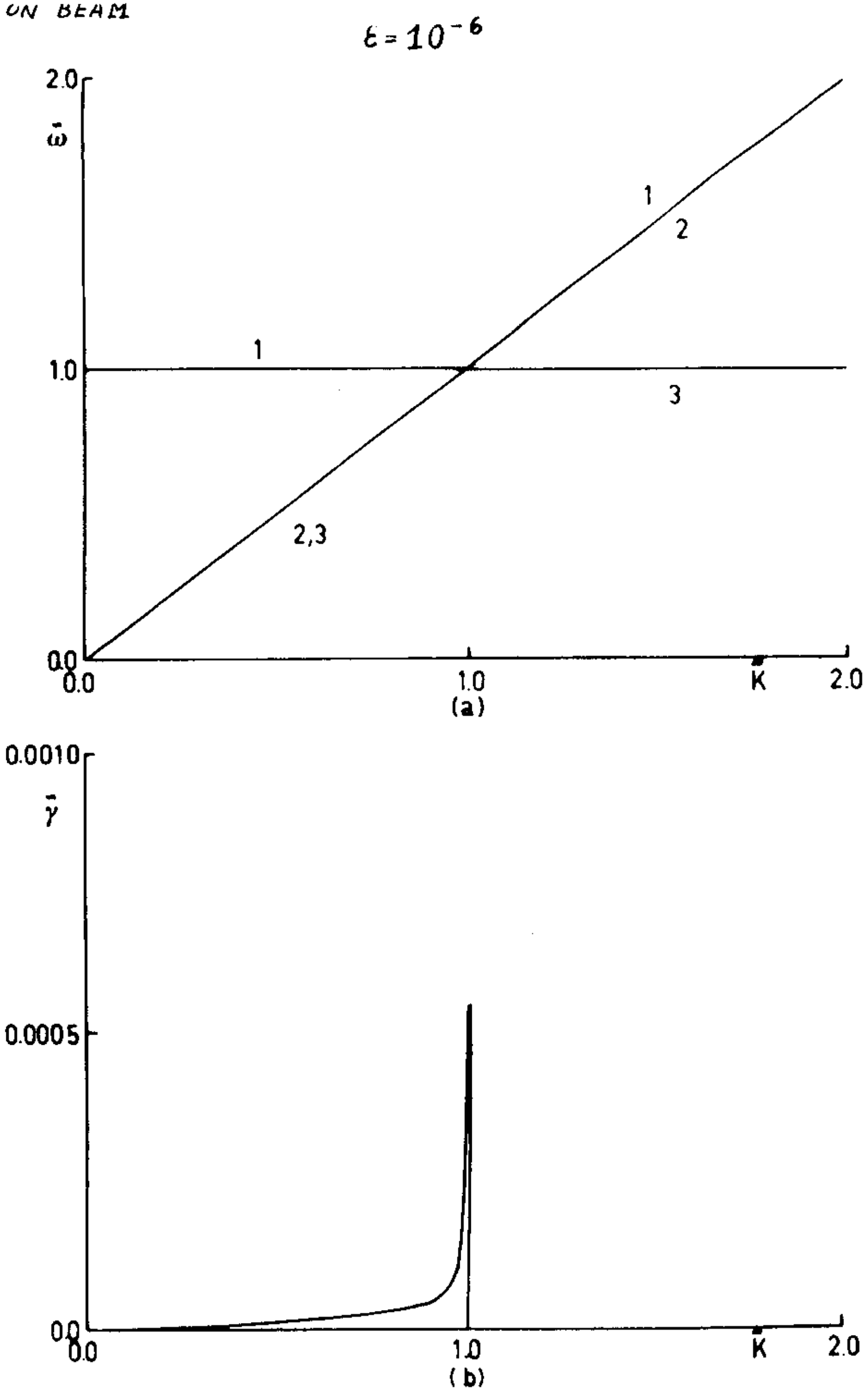
In the Figures the oscillation branches (identified by digits) are plotted in panels (a) and the corresponding growth rates in panels (b).
The high-frequency plasma branch (1) can be easily identified. The resonance branch (2) represents the unstable beam-plasma oscillations ($\tilde{\gamma} > 0$).

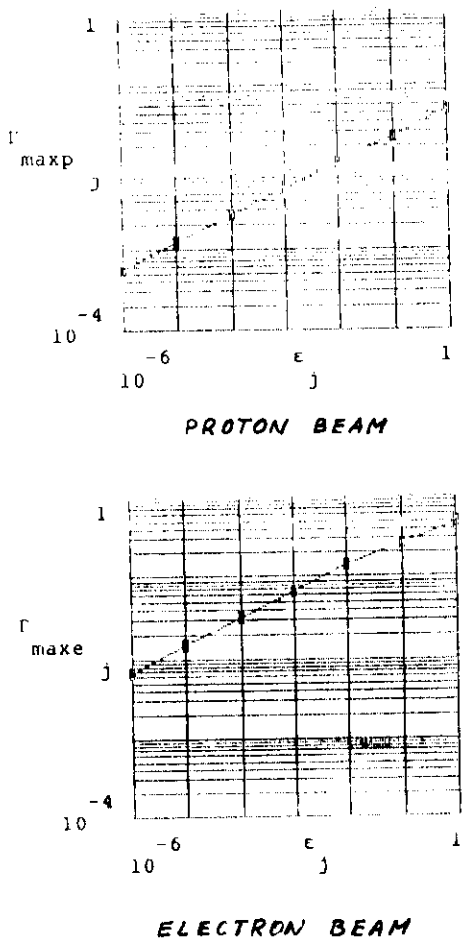
As the beam density is decreased, the range of wavevectors corresponding to an appreciable amplitude of the growth rate $\tilde{\gamma}$ is reduced and such is also the maximum growth rate (see following graphs).

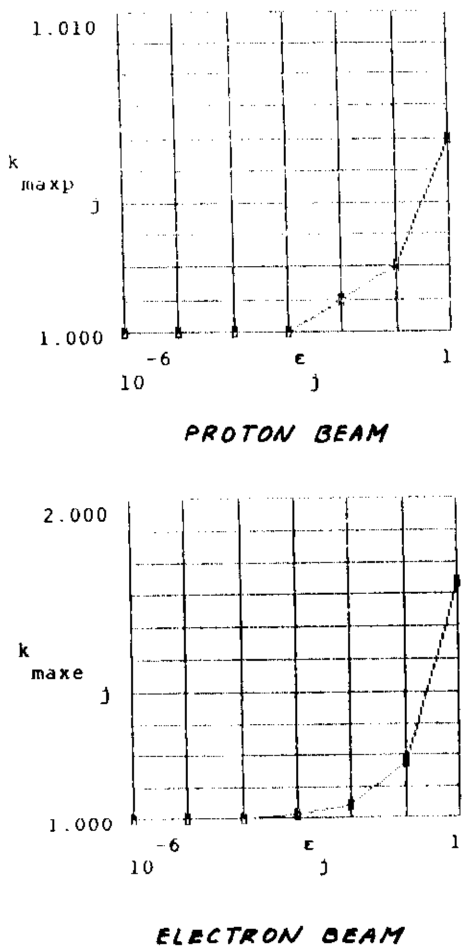


(a)
(b)

PROTON BEAM

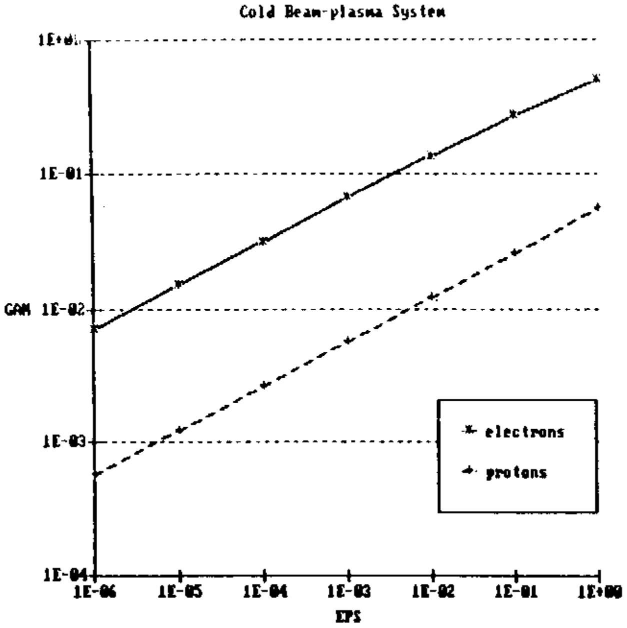






Maximum linear growth rate γ vs. beam density $\varepsilon = \frac{n_b}{n_0}$ in the electrostatic case

Maximum normalized wavevector $\tilde{k} = kV_b/\omega_{pe}$ vs. beam density ε in the electrostatic case



Linear growth rate γ vs. beam density $\varepsilon = n_b / n_0$ for electron and proton beams in the electrostatic 1-D case

From a direct comparison of the growth rates in the PROTON and in the ELECTRON case it comes out that the FORMER is 1 order of magnitude LOWER. This is in agreement with the analytical analysis (see e.g. Mikhailovskii, 1974) that shows that in the case of proton beams the growth rate is reduced by a factor $(MRP)^{1/3} \propto 12$.

It is impossible to draw a conclusion about the possible radioemission by proton beams from such a simple analysis, because the used approximations are quite restrictive and the temperature spread must be taken into account. Moreover the NON-LINEAR evolution of the system must be considered in order to determine the SATURATION LEVEL of the instability. Such energy level is a fundamental parameter in the radio emission process in order to establish the available energy in the plasma waves to be converted into transversal electromagnetic waves.

BEAM PARTICLE TRAPPING

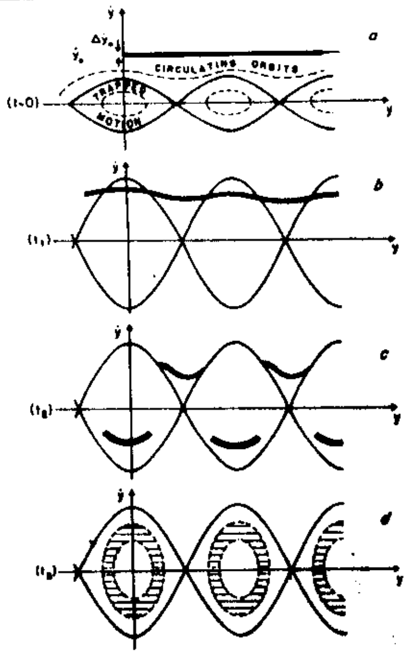


Fig. 2. A quasi-monokinetic electron beam (mean velocity $\dot y_0$, velocity dispersion $\Delta \dot y_0$, in the resonant frame) destabilizes a quasi monochromatic wave. This leads to the possibility of trapping motion in the electronic phase space (Figure 2(a)), here sketched in the resonant frame. When the wave grows further, the size of the trapping cells (delimited by the full-lined separatrix) increases until the destabilizing beam become trapped (at time t_1, Figure 2(b)). The electron of the beam then rotate in phase space (time $t_2 > t_1$, Figure 2(c)), until the distribution is smoothed such that equally number of electrons give energy to the wave and take energy from it, then leading to the saturation of the instability (Figure 2(d)).

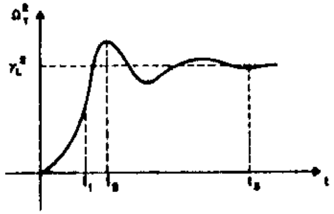
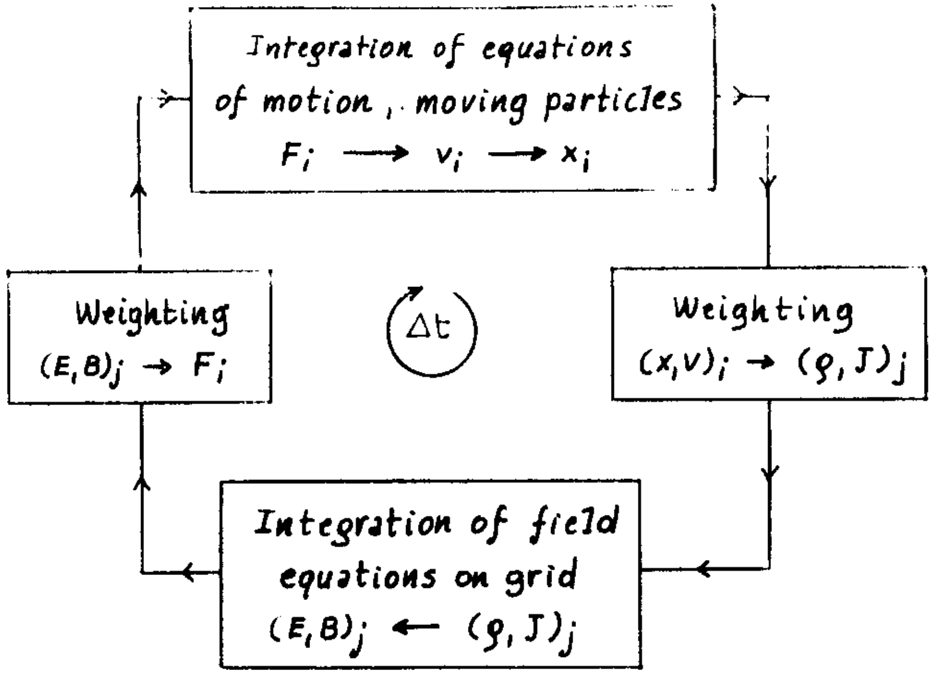


Fig. 3. Schematic view of the evolution of the unstable wave amplitude (or trapping pulsation), during the trapping type saturation process. Times t_1, t_2, and t_3 schematically correspond to those of Figure 2 Oscillations at the trapping frequency finally damp away, due to the mixing phenomena described in the text.

(from Le Queau & Roux, 1987)

THE TYPICAL COMPUTATIONAL CYCLE

ONE TIME STEP in a PARTICLE SIMULATION CODE

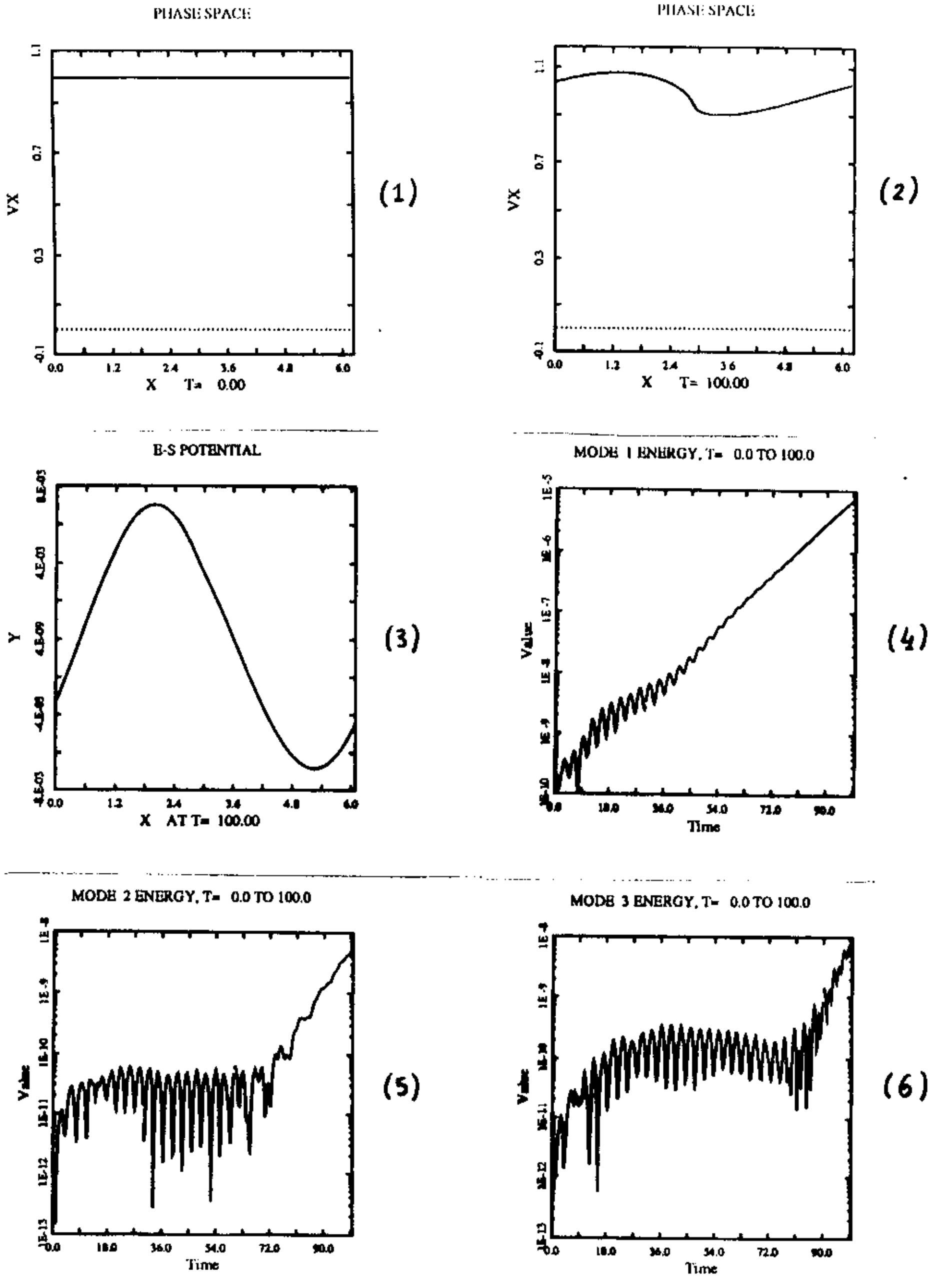


$i = 1, 2, .. NP$ PARTICLES

$j = 1, 2, .. NG$ GRID POINTS

(from Birdsall & Langdon, 1985)

Beam-plasma instability: NON-LINEAR EVOLUTION



OUTPUT of the electrostatic code ES1

DIFFERENT DIAGNOSTICS:

THE APPLICATION OF A 1-D ELECTROSTATIC CODE FOR THE ANALYSIS OF BEAM-PLASMA SYSTEMS IN THE SOLAR CORONA

M. Messerotti[1], M. Karlicky[2], P. Zlobec[1]

(1) Astronomical Observatory, Trieste, Italy

(2) Astronomical Observatory, Ondrejov, Czechoslovakia

SOMMARIO

Si discute l'uso di un codice elettrostatico unidimensionale per l'analisi di sistemi fascio-plasma. Si e' condotto uno studio preliminare di un'instabilita' elettrostatica di streaming di tipo "bump-on-tail" nel regime non lineare per un fascio di protoni ed uno di elettroni aventi la stessa densita' e velocita' nel caso freddo. L'energia di saturazione ottenuta per i protoni e' superiore a quella degli elettroni, il che suggerisce una possibilita' di radioemissione anche per il primo tipo di particelle.

ABSTRACT

The use of a particle simulation code for the analysis of beam-plasma systems is discussed. The code is one-dimensional and electrostatic. Such a code has been used in a preliminary study of an electrostatic streaming instability (bump-on-tail type) in the nonlinear regime and the related choice of system parameters is explained. The saturation of the instability is analyzed for a proton as well as for an electron weak beam having the same density and velocity in the cold approximation and the correspondent energy levels are compared to test the efficiency of the process. The saturation level for protons revealed to be larger than that of electrons. This is suggestive of a possible radioemission by protons.

Introduction

In solar radioastronomy various kinds of radio bursts observed in the metric and decimetric band are interpreted on the basis of the plasma radiation mechanism: some type of plasma instability generates high-frequency plasma oscillations (Langmuir waves), which are converted into observable radio waves via a nonlinear process (e.g. Melrose, 1987).

This mechanism seems to explain quite well the type III bursts, which are the signature of an electron beam injected into the coronal plasma after acceleration during the impulsive phase of a flare. Such a beam is propagating with a velocity of approximately c/3 and excites plasma waves at different coronal levels (i.e. plasma frequencies) giving origin to a frequency drifting radioemission. This instability is the so-called "beam-plasma instability" and it is quite effective for an electron beam. Many studies were devoted to the theoretical investigation of these systems (Melrose, 1980 and references therein).

Recent observations from the SMM satellite pointed out that protons and electrons are quasi-simultaneously accelerated during the impulsive phase of flares and in the literature it is suggested that proton beams can be the exciter of low-drift radio bursts (Benz and Simnett, 1986). So it is worthwile theoretically considering proton-beam plasma systems to determine if they are suitable candidates for radioemission.

The linear regime for a three component plasma (beam protons, plasma electrons and protons) in the zero temperature approximation was analyzed e.g. in Messerotti (1987) for the electrostatic case. From this analysis one can get the most unstable mode and the corresponding maximum growth rate (see Figure 1), but nothing can be said about the further developement of the system. This is a problem as the energy level of growing waves is an important parameter in estimating the radio intensity of observed bursts and on a relatively long time-scale trapping effects become effective and must be taken into account in determining such level. With regard to that the linear regime does

not provide an appropriate description and one must look at the nonlinear phase (see e.g. Le Queaux and Roux, 1987).

The particle trapping for a proton as well as for an electron beam having the same density and velocity is considered in the following as a preliminary approach to the problem by using the saturation times and energies obtained by a particle simulation code in comparison to those provided by the analytical theory. The agreement is quite satisfactory notwithstanding the inadequate description of the physical system used in the simulation to shorten the running time.

The simulation parameters

The particle simulation code "ES1" documented in Birdsall and Langdon (1985) was used. It is an electrostatic code which allows the addition of a static magnetic field and provides many useful diagnostics to analyze the system evolution such as the time histories of the energy in the various modes.

A beam-plasma system was simulated on a relatively long time-scale first for an electron stream (1200 time steps) and then for a proton stream (2600 time steps) interacting with a background electron plasma (the neutralizing ion background is added by default). The beam density was chosen as 10^{-3} the background density (weak-beam model). The proton mass was set to 10 times the electron mass to reduce the computing time, but this value is probably to low to give a good description of a real proton beam and it will be changed to 100 in future runs. The number of grid points was set to 64 as the number of background electrons, while the beam particle number having to be greater to reproduce adequately the trapping effects was set to 512. The lenght of the system, which is the wavelenght of the most unstable wave, was set to 2π to place the first mode near the peak of the growth rate determined by the linear analysis. To this mode a small initial perturbation was given. For a detailed discussion of such values see Birdsall and Langdon (1985, p. 119).

The time history of the electrostatic energy for the first mode ($\tilde{k} = k\, V_b / \omega_{pe} = 1$) is given in Figure 2 for an electron and in Figure 3 for a proton beam. The energy levels at the first peak were assumed as saturation values to be compared with the theoretical estimations.

Theoretical estimations

The growth rate of a beam-plasma system in the case of longitudinal electrostatic oscillations is:

$$\gamma_L = \omega_{pe} \frac{\sqrt{3}}{2^{4/3}} \left[\frac{n_b}{n_o} \right]^{1/3} \left[\frac{m_e}{m_b} \right]^{1/3} \qquad [1]$$

where ω_{pe} is the electron plasma frequency, (n_b / n_o) is the beam to plasma density ratio and (m_e / m_b) is the electron to beam particle mass ratio.

The trapping period for beam particles (Le Queaux and Roux, 1987) is:

$$T = \frac{2\pi}{\Omega_T} = 2\pi \left[\frac{m_b}{keE} \right]^{1/2} \qquad [2]$$

with Ω_T - trapping frequency, k - wavenumber and E - electric field intensity at saturation.

The saturation level of the field energy densities given by (Birdsall and Langdon, 1985, p. 117):

$$W(t_2) = \frac{1}{4} \varepsilon_o E^2(t_2) = \left[\frac{R}{2} \right]^{1/3} \left[\frac{1}{2} m_b n_b v_o^2 \right] \qquad [3]$$

with t_2 - trapping time, $R = (\omega_{pb} / \omega_{pe})^2 \propto (n_b / n_o)$ - beam to electron plasma frequency ratio and v_o - streaming velocity. Hence one can write:

$$E^2(t_2) \propto R^{1/3} m_b \propto m_b^{2/3} \rightarrow E(t_2) \propto m_b^{1/3} \qquad [4]$$

and the ratio of the trapping periods between protons and electrons become:

$$\frac{T_p}{T_e} = \left(\frac{m_b}{m_e} \right)^{1/3} . \qquad [5]$$

From [3] and [4] one can estimate the ratio between the saturation levels:

$$W \propto E^2 \propto m_b^{2/3} \rightarrow \frac{W_s^p}{W_s^e} \propto \left(\frac{m_p}{m_e} \right)^{2/3} . \qquad [6]$$

For (m_b / $m_e \simeq 1843$) one gets a ratio equals to 150, which means that the saturation level for protons is two orders of magnitude higher than that of electrons.

Comparison of theoretical estimations and numerical results

In Table I a comparison between the theoretical values and the numerical ones is reported. As one can see the agreement is quite satisfactory for the chosen mass ratio for protons (m_b / m_e = 10). A discrepancy was obtained in a preliminary run with a mass ratio equals to 100, but this can be due to the fact that augmenting this parameter requires also a higher number of particles to describe properly the beam on a long time-scale. This modifications will be the goal of future simulations, when the program will be implemented on a dedicated workstation so allowing to disregard the running time.

Conclusion

The nonlinear regime of a beam-plasma system was studied for different beam particles by using the analytical approach as well as the simulation one. Results derived according to both procedures are in satisfactory agreement, so confirming the validity of going on simulating with different parameters of the system to provide an extensive analysis, which can find an interesting application to solar radioastronomy.

These preliminary results show that the saturation level of proton beams is 150 times higher than that of electron beams (having the same density and velocity) propagating in a background plasma. This means that the efficiency of conversion between beam kinetic energy and plasma waves energy is higher for protons. Such a fact is interesting if compared with the result given by the linear analysis, which gives a growth rate for protons one order of magnitude smaller than that of electrons.

Even if this would support the hypothesis that protons can be suitable candidates for radioemission in solar conditions, one must be careful in drawing conclusions because in these preliminary simulations it was not considered the trapping of background electrons, which can be effective in some situations giving a lower level of plasma waves in the case of a proton beam. Such effects can be simulated but one must be very careful in the choice of correct mass ratio and number of particles.

Acknowledgements

This work was partially supported by the Italian National Research Council (CNR).

The computations were carried out at the computing centre of the International School for Advanced Studies of Trieste (SISSA) and at the ASTRONET Pole of the Astronomical Observatory of Trieste.

References

Benz, A.O., Simnett, G.M.: 1986, Nature 320, 508.

Birdsall, C.K., Langdon, A.B.: 1985, "Plasma Physics via Computer Simulation", McGraw-Hill Inc.

Le Queau, D., Roux, A.: 1987, Solar Phys. 111, 59.

Melrose, D.B.: 1980, "Plasma Astrophysics", Gordon and Breach Science Publ., New York, Vol. I and II.

Melrose, D.B.: 1987, Solar Phys. 111, 89.

Messerotti, M.: 1987, Hvar Obs. Bull. 11, 125.

Table I

	Electrons	Protons
GROWTH RATE in the linear phase		
Theory	0.0687	0.0319
Numer.	0.0636	0.0310
SATURATION LEVEL at first peak		
Theory	2.493 E -4	1.157 E -3
Numer.	2.938 E -4	1.480 E -3
RATIO between SATURATION LEVELS		
Theory		4.64
Numer.		5.04
TRAPPING PERIOD		
Theory	55.9	120.2
Numer.	61.6	130.8
RATIO between TRAPPING PERIODS		
Theory		2.15
Numer.		2.12

In the theoretical estimations a mass ratio for protons equals to 10 has been assumed.

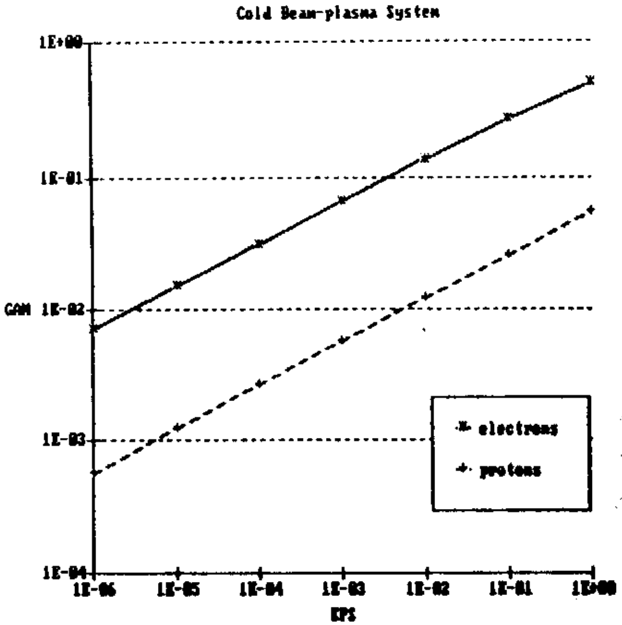


Fig. 1 - Maximum growth rate as a function of beam density (normalized to the plasma density) in the linear regime for electrons and protons.

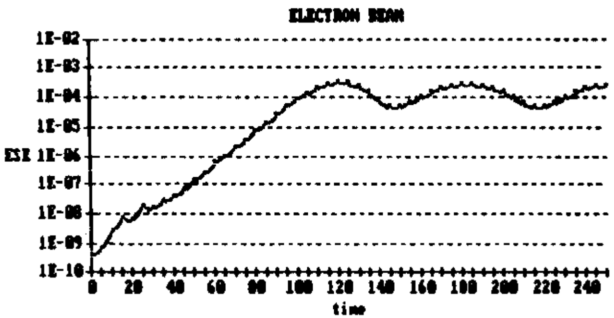


Fig. 2 - Electrostatic energy time history for an electron-beam plasma system in the nonlinear regime as produced by the program ES1 (see text)

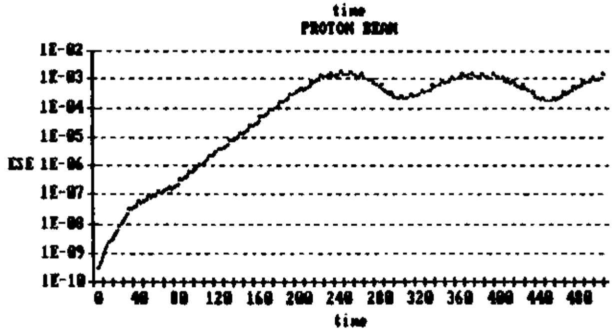


Fig. 3 - Electrostatic energy time history for a proton-beam plasma system in the nonlinear regime as produced by the program ES1 (see text).

References (BOOKS)

Kundu, M.R.: 1965, 'Solar Radio Astronomy', Interscience, New York.

Kaplan, S.A., Tsytovich, V.N.: 1973, 'Plasma Astrophysics', Pergamon Press, Oxford

Krüger, A.: 1979, 'Introduction to Solar Radio Astronomy and Radio Physics', D. Reidel Publ. Co., Dordrecht, Holland

McLean, D.J., Labrum, N.R.: 1985, 'Solar Radiophysics', Cambridge University Press, Cambridge

Mikhailovskii, A.B.: 1974, 'Theory of Plasma Instabilities', Vol. 1 and 2, Consultants Bureau, New York

Melrose, D.B.: 1980, 'Plasma Astrophysics', Vol. 1 and 2, Gordon and Breach Science Publ., New York

Hockney, R.W., Eastwood, J.W.: 1981, 'Computer Simulation using Particles', McGraw-Hill, New York

Birdsall, C.K., Langdon, A.B.: 1985, 'Plasma Physics via Computer Simulation', McGraw-Hill, New York.

References (Journals)

Ambrož, P.: 1983, in 'Noise Storm Coorolinated Observations', Oslo University, Norway, 171

Benz, A.O., Simnett, G.M.: 1986, Nature 320, 508

Chupp, E.L.: 1983, Solar Phys. 86, 383

Dulk, G.A.: 1985, Ann. Rev. Astron. Astrophys. 23, 169 [a general review on solar radio astronomy with many references]

Ramaty, R., Murphy, R.J., Kozlovsky, B., Lingenfelter, R.E.: 1983, Solar Phys. 86, 395.