Synchrotron radiation from charge separation instabilities in the early universe.

Soma Sanyal
School of Physics, University of Hyderabad
Prof.C.R.Rao Road, Hyderabad, India 500046

Outline of the talk

- Plasma scales and instabilities
- Charge separation in magnetized plasmas
- Generation of charge instabilities
- Electric fields due to charge instabilities
- Synchrotron radiation from accelerated charged particles in the plasma

Plasma Scales and Instabilities

- Three major scales involved when studying plasma magnetohydrodynamics in the early universe
- Macroscale describes the large scale dynamics of the plasma (typically of the order of the horizon)
- Microscale describes the kinetic regime where particle interactions are important
- There is a scale connecting the microscopic kinetic quantities to the overall macroscale dynamics of the plasma. This is known as the mesoscale
- For a magnetized plasma, the momentum and heat transport are highly anisotropic with respect to the magnetic field direction
- This leads to a host of superfast microscale instabilities in the plasma

Ref: A. A. Schekochihin et. al, MNRAS 405, 291 – 300 (2010)

Plasma Scales and Instabilities

- Microscale instabilities occur due to pressure, temperature and velocity anisotropies
- The microscale plasma fluctuations lead to plasma turbulence on the mesoscale
- In the macroscopic scale, the cosmological plasma is essentially charge neutral
- However charge fluctuations do exist on microscale levels
- Such charge fluctuations may be responsible for the seed magnetic fields that were later amplified and gave rise to the observed magnetic fields in our universe

Ref : S. J. Schwartz et. al Space Sci. Rev. 178: 81-99 (2013)

Charge separation in magnetized plasmas

- A plasma is considered magnetized when the collisional frequency of the charged particles are smaller than the Larmor frequency in the given magnetic field
- Charge separation generates a strong electric field in the plasma
- The cosmological plasma has a very high conductivity. Strong electric fields generated in the plasma will set up plasma oscillations eventually dissipating the energy of the electric field
- But at small scales, much smaller than the mean free path of the charged particles, it is possible to have charge instabilities.
- These instabilities have growth rates proportional to k so the equations for macroscopic dynamics derived in the long wavelength limit will have problems
- It is a multiscale problem and difficult to tackle analytically as well as numerically

Ref : A. G. Oreshko, Doklady Physics, Vol 46 No 1 pp 9-11 (2001)

Generation of charge instabilities

The equation of continuity for the charged particles in the FRW metric would be

$$\frac{\partial N_c}{\partial t} + \theta N_c + \frac{\partial (N_c U_c^i)}{\partial x^i} = 0 \qquad \text{where} \qquad \theta = 3\frac{\dot{a}}{a}$$

We have considered the net charge density and a small velocity difference between the negatively and positively charged particles.
The momentum equation in the presence of the electromagnetic field is given by

$$\frac{\partial U^i}{\partial t} = \frac{q}{m_e}\left(E^i + \epsilon_{ijk} U^j B^k\right) - \frac{2\theta}{3} U^i - U^j \frac{\partial U^i}{\partial x^j} - \frac{1}{m_e N_{tot}} \frac{\partial P^{ij}}{\partial x^j}.$$

We use the linear perturbation technique and give a small perturbation to the Net charge density

Ref: Dodin et al, Phys.Rev. D 82,044044 (2010)

Generation of charge instabilities

- For transverse waves, we can drop the pressure terms
- We also divide throughout by the initial charge number density to make the variable dimensionless

$$\frac{\partial^2 n}{\partial t^2} + \frac{2\theta}{3}\frac{\partial n}{\partial t} + \omega_p^2 n + \frac{f\,q}{2\,m_e}\left(\Omega^k B^k + U^i \epsilon_{ijk}\frac{\partial B^k}{\partial x^j}\right) = 0.$$

Plasma frequency — Vorticity

- Depending on the velocity anisotropy and the magnetic field direction we obtain the various equations for the charge fluctuations

Ref: N. A. Krall and A. W. Trivelpiece, Principles of Plasma Physics (McGraw-Hill, New York) 1973

Charge Fluctuations

- Velocity perturbation along x-direction, magnetic field constant along the z- direction

$$\frac{\partial^2 n}{\partial t^2}+\frac{2\theta}{3}\frac{\partial n}{\partial t}+\omega_p^2 n+\frac{q\, f\, \Omega^z B_0}{2 m_e}=0$$

- Bulk velocity in a given direction is constant, magnetic field no longer constant

$$\frac{\partial^2 n}{\partial t^2}+\frac{2\theta}{3}\frac{\partial n}{\partial t}+\omega_p^2 n+\frac{q\, f}{2 m_e} V_a\left(\frac{\partial E_i}{\partial t}+\theta E^i\right)=0$$

- From these we obtain the dispersion relation for a plane wave

The Dispersion Relations

- Velocity perturbation along x-direction, magnetic field constant along the z- direction

$$\omega = \frac{-i\theta}{3} \pm \sqrt{\frac{-\theta^2}{9} + \omega_p^2 + i\frac{q f B_0 k}{2 m_e}}$$

- Bulk velocity in a given direction is constant, magnetic field no longer constant

$$\omega = \frac{-i}{2}\left(\frac{2}{3}\theta + \frac{q f}{2 m_e} V_a\right) \pm \sqrt{-\left(\frac{\theta}{3} + \frac{q f}{4 m_e} V_a\right)^2 + \omega_p^2 + \frac{q f}{2 m_e} V_a \theta}$$

Charge Instability

- Condition for charge instability

$$\sqrt{\frac{-\theta^2}{9}+\omega_p^2+i\frac{q\,f\,B_0\,k}{2\,m_e}}=X+i\,Y$$

- Y should be real and positive

$$Y^2=\frac{1}{2}\left(\left(\frac{\theta^2}{9}-\omega_p^2\right)\pm\sqrt{\left(\frac{\theta^2}{9}-\omega_p^2\right)^2+\left(\frac{q\,f\,B_0\,k}{2\,m_e}\right)^2}\right)$$

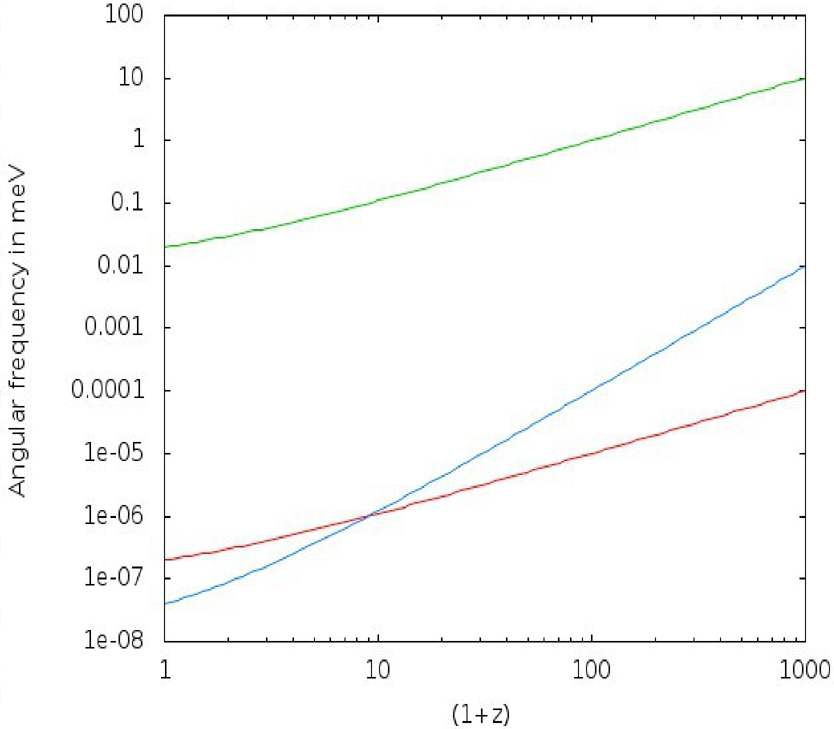
$$\left(\frac{q\,f\,B_0\,k}{2\,m_e}\right)^2\gg\omega_p^2$$

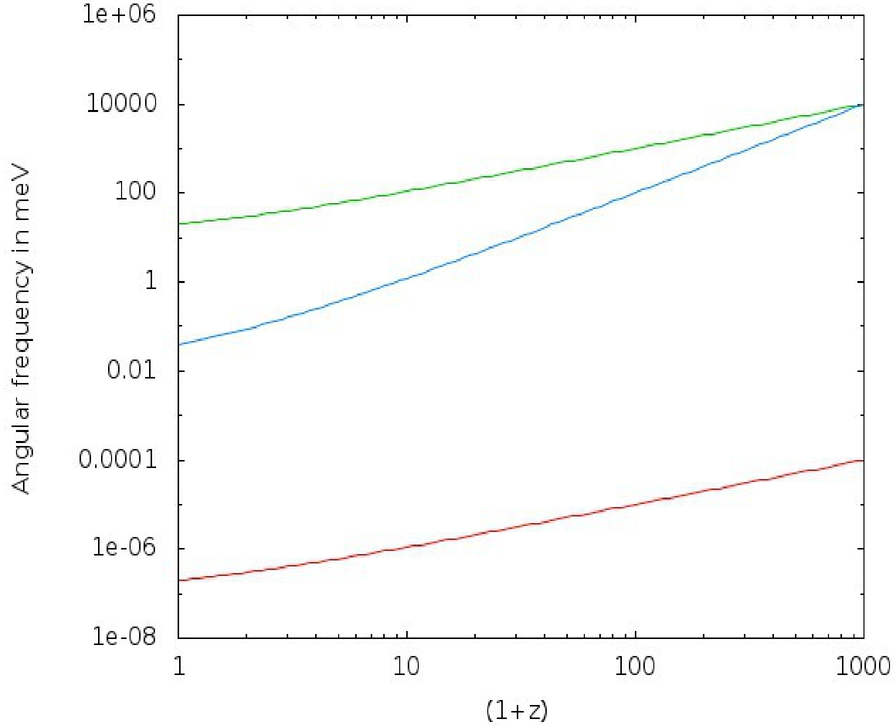
Generation of the electric field

- The charge instability leads to a strong electric field over short lengthscales
- Strong electric fields are damped by the electron oscillations in the plasma
- All these depend on the lengthscales that we are considering
- There are three lengthscales involved here.
- Lengthscale of the magnetic field (Given by $\omega_B = \frac{e B}{m}$)
- Lengthscale given by the plasma frequency
- Lengthscale of the instability
- All these depend on the temperature and the magnetic field, hence the redshift parameter (1+ z)

Evolution of the lengthscales for different magnetic fields

For B = 1 Gauss and B = 1 microGauss





Red -- Plasma frequency, Blue – Gyrofrequency , Green – Instability

The Electric field

- The electric field will give rise to space charge only if

$$\omega_{un} \gg \omega_p$$

- We can obtain the electric field using Maxwell's equation and the critical density

$$n_{crit} = \frac{\omega_{un}^2 \epsilon_0 m}{e^2}$$

$$E = \frac{\epsilon_0 m_e}{e^2} \left(\frac{e f B_0 k}{2 m_e} \right)^2$$

Synchrotron radiation

- Instability generates an electric field over a short lengthscale
- Magnetic field is constant over this patch
- Mean free path of the charged particles is very large compared to the size of these patches.
- As the particles move through the patches, they are accelerated by the electromagnetic field and emit synchrotron radiation
- Spectrum of the radiation depends on the gamma factor obtained from the Poynting vector
- We have already obtained the electric field density. Assuming a constant magnetic field density we obtain the gamma factor

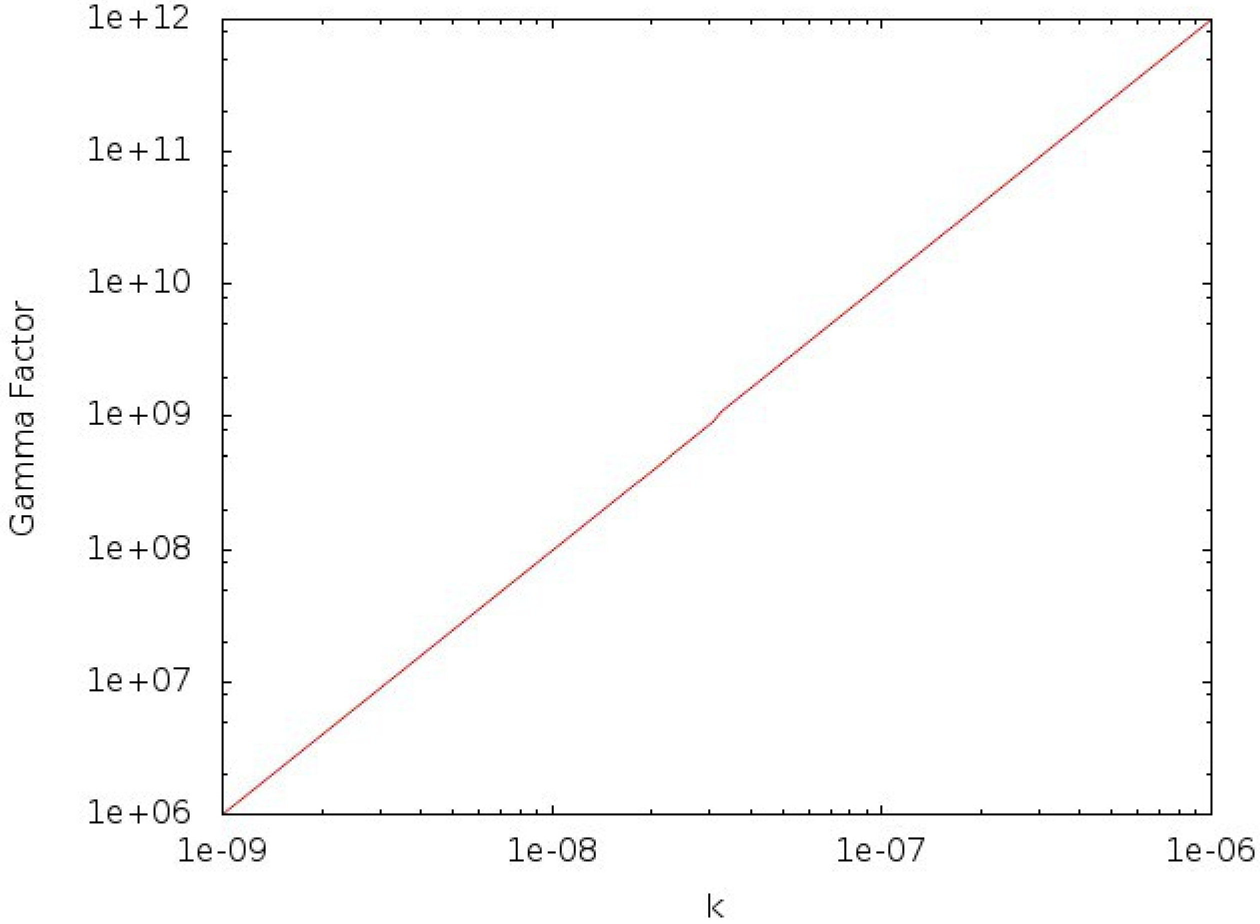
The Gamma Factor

- The gamma factor is given by

$$\gamma = \left(\frac{f^2 k^2 B_0 k}{2 m_e} \right)^2 \frac{B_0}{e^2} l^6$$

- Here *l* gives the lengthscale of the patch
- Gamma factor depends on the magnetic field strength and the wavelength.
- We obtain very large gamma factors even for small magnetic fields

Gamma Values for different wavelengths



Synchrotron Radiation

- For a given gamma factor, the critical frequency for the synchrotron radiation is proportional to the cubic power of gamma
- For gamma factors of this range, the critical frequency is of the order of

$$\omega_c \sim 10^8\, MHz$$

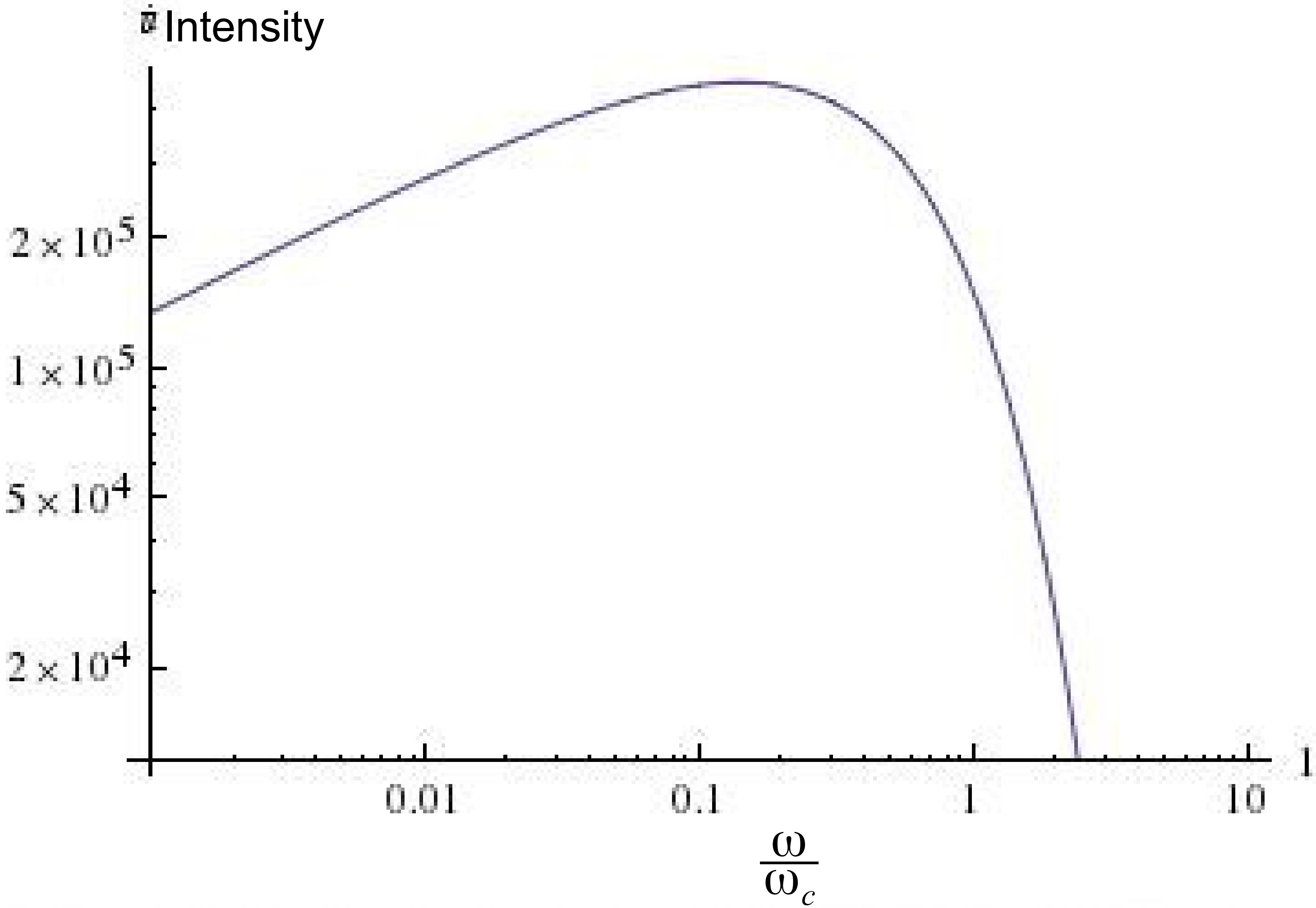
- The spectrum is given by

$$\frac{dI}{d\omega} = 2\sqrt{3} e^2 \gamma \frac{\omega}{\omega_c} \int_{\frac{2\omega}{\omega_c}}^{\infty} K_{5/3}(x)\, dx$$

- We plot the spectrum for

$$\gamma = 10^6$$

Synchrotron radiation spectrum



Conclusions

- Microinstabilities in the plasma may generate large electric fields at small scales
- Due to the large mean free path of the charged particles, the plasma can be treated as collisionless over small lengthscales
- Presence of a magnetic field as well as an electric field will result in acceleration of the charged particles over small patches
- As they are accelerated they emit synchrotron radiation which has a distinct signature
- Next goal : try to see if the obtained synchrotron radiation matches any of the observational spectrum