RADIO DETECTION OF GREEN PEAS: IMPLICATIONS FOR MAGNETIC FIELDS IN YOUNG GALAXIES

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RADIO DETECTION OF GREEN PEAS: IMPLICATIONS FOR MAGNETIC FIELDS IN YOUNG GALAXIES

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ABSTRACT

Green Peas are a new class of young, emission line galaxies that were discovered by citizen volunteers in the Galaxy Zoo project. Their low stellar mass, low metallicity, and very high star formation rates make Green Peas the nearby (z ~ 0.2) analogs of the Lyman break galaxies which account for the bulk of the star formation in the early universe (z ~ 2–5). They thus provide accessible laboratories in the nearby universe for understanding star formation, supernova feedback, particle acceleration, and magnetic field amplification in early galaxies. We report the first direct radio detection of Green Peas with low frequency Giant Metrewave Radio Telescope observations and our stacking detection with archival Very Large Array FIRST data. We show that the radio emission implies that these extremely young galaxies already have magnetic fields (≥30 μG) even larger than that of the Milky Way. This is at odds with the present understanding of magnetic field growth based on amplification of seed fields by dynamo action over a galaxy’s lifetime. Our observations strongly favor models with pregalactic magnetic fields at μG levels.

Key words: cosmic rays – galaxies: magnetic fields – galaxies: starburst – radio continuum: galaxies

Online-only material: color figures

1. INTRODUCTION

A new class of young emission line galaxies, named Green Peas (Cardamone et al. 2009), was recently discovered by volunteers in the Galaxy Zoo project (Lintott et al. 2008). They are interesting because of their small size and their extraordinarily large [OIII] equivalent width (up to ~1000 Å; see Figure 1), which indicates a large population of young stars. Typical Green Peas have r ~ 20, u – r ~ 0.9, and z ~ 0.2 (Cardamone et al. 2009). They are low-mass galaxies (M ~ 10^8–10^9 M⊙) with high star formation rates (SFRs; ~10 M⊙ yr⁻¹). Hence, they have some of the highest specific SFRs (M/M⊙ of up to ~10^5 yr⁻¹) were obtained by Cardamone et al. (2009) seen in the local universe. This indicates very short stellar mass doubling times (t_{double} ~ 10^8 yr), compared to typical star-forming galaxies (t_{double} ~ 10^10 yr). Due to their small reddening (E(B – V) ≤ 0.25) and luminous UV emission this class of star-forming galaxies is similar to UV luminous galaxies observed at high redshift (z ~ 2–5). Their relatively low metallicities (log[O/H] + 12 ~ 8.7; 8.7) and locations in underdense environments suggest that Green Peas started building their stellar content at z ~ 0.2 by processes similar to those experienced by high-redshift Lyα emitters and Lyman break galaxies (LBGs; see Giavalisco 2002 for a review). Green Peas may have systematically larger [N/O] ratios, and therefore potentially even lower metallicity (Amorín et al. 2010) than reported by Cardamone et al. (2009).

Green Peas are unresolved by the Sloan Digital Sky Survey (SDSS), implying typical angular sizes ≤1″ and gives physical sizes ≤5 kpc. Their patchy irregular appearance in resolved Hubble Space Telescope (HST) snapshots, possibly due to compact star-forming regions (Cardamone et al. 2009), mimics the morphologies of high-redshift galaxies. Given high SFRs, Green Peas are expected to host a large number of supernovae. Supernovae accelerate electrons, which emit synchrotron radiation in radio bands. We have stacked archival Very Large Array (VLA)

FIRST (Becker et al. 1995) data at 1.4 GHz to demonstrate that their fluxes are systematically lower than those of usual starburst galaxies but are statistically akin to those of LBGs, which have systematically lower fluxes than local starbursts at a given SFR (Carilli et al. 2008). We have followed up three Green Peas with deep observations at 0.6 GHz using the Giant Metrewave Radio Telescope (GMRT). In this Letter, we establish Green Peas as a new class of sub-milliJansky sources in the GHz radio sky. We use theoretical considerations to show that these radio detections imply large magnetic fields for Green Peas. This raises puzzling questions about the nature of magnetic fields in young galaxies: Were there μG level pre-galactic fields? Is the dynamo effect faster than anticipated?

2. RADIO EMISSION IN GALAXIES

Radio emission from most normal galaxies is due to synchrotron radiation of relativistic electrons and free-free emission of ionized hydrogen (H II) regions (Condon 1992). Both are produced by massive stars (M > 8 M⊙) which end their bright but short lives (t < 3 × 10⁷ yr) in supernovae. During their lifetimes these stars ionize the surrounding interstellar medium (ISM) and create H II regions. Shocks produced by supernovae accelerate a majority of the relativistic electrons in normal galaxies. These electrons have short lifetimes (t < 10⁸ yr); hence radio emission in a normal galaxy traces recent star formation activity.

The nonthermal radio brightness of a typical star-forming galaxy is given by Yun & Carilli (2002) as

\[ S_{\text{nth}}(\nu) = 25 f_{\text{nth}} \nu^{-α} \left( \frac{\text{SFR}}{M_⊙ \text{yr}^{-1}} \right) D_L^{-2} \text{ Jy}, \]

where \( f_{\text{nth}} \) is the nonthermal fraction of the SFR. Equation (1) represents the relation between the nonthermal radio luminosity and the SFR in units of Jy. The factor \( f_{\text{nth}} \) is typically on the order of 0.5, depending on the efficiency of the magnetic field amplification process. For a typical star-forming galaxy, the radio luminosity is directly proportional to the SFR, \( M_⊙ \text{yr}^{-1} \), and inversely proportional to the luminosity distance, \( D_L \), which is the distance to the galaxy.

4 Here, normal (Condon 1992) refers to nearby galaxies in which the radio emission is not dominated by a central super-massive black hole. Seyfert Peas (Cardamone et al. 2009) are excluded from this study and we only concentrate on star-forming Peas.
where $D_L$ is luminosity distance in Mpc. Variations in the normalization of the nonthermal synchrotron emission are traced by $f_{nth}$, which is $\sim 1$ for the Milky Way and local starbursts (Yun & Carilli 2002). With high SFRs, young star-forming galaxies like LBGs and Green Peas are expected to have some nonthermal radio emission. However, to date no direct radio emission has been reported. In LBGs (Carilli et al. 2008) and their analogs (Basu-Zych et al. 2007), stacking techniques have
been used to overcome their faintness. With Green Peas, we have a local sample to search for their radio emission both by stacking existing VLA data (Section 3) and by additional observations with GMRT (Section 4).

3. VLA FIRST STACKING DETECTION

Highest estimated fluxes for Green Peas are a factor of $\sim 2$ short of the VLA FIRST survey threshold of $\sim 1$ mJy (Becker et al. 1995) at 1.4 GHz, so they need to be detected by stacking. See White et al. (2007) for extensive discussion of techniques for stacking FIRST images to detect sources below the survey threshold. Conventional wisdom suggests that summing up $N$ images of faint objects produces an increase in the signal-to-noise ratio ($S/N$) of $\sqrt{N}$. This implies that stacking all available objects is the best strategy. However, this strategy can be bettered if a flux estimate is available. We estimate the expected fluxes of all 80 spectroscopically identified star-forming Green Peas from Cardamone et al. (2009) using Equation (1) with $f_{\text{nth}} = 1$ in a flat CDM cosmology with $h = 0.71$ and $\Omega_M = 0.3$, with SFRs derived from their optical spectra (see Figure 1). In this situation it is best to stack the $N$ galaxies with the highest expected fluxes. In Figure 2, we show that the $S/N$ rises rapidly in the range $N \sim 1–15$ and falls off slowly beyond $N \gtrsim 30$. We therefore stack $N = 2^5$ (the nearest power of 2) of the brightest expected Green Peas.

The images of these $N$ regions were cut out and summed in pairs, with this process being repeatedly applied to the resulting $N/2$ maps until the final map was obtained. This was done to avoid a sequential summation, which results in the addition of large floating point numbers with small ones in the latter steps, leading to accumulation of roundoff errors. The final image (after adding and dividing by $N$) has Gaussian noise with $\sigma = 0.027$ mJy. The convergence of the sample mean to the population mean is unbiased and faster than the convergence of the sample median to the population median (Kenney & Keeping 1957). The stacked mean flux is found to be $0.124 \pm 0.027$ mJy (compare with the median stacked detection in Figure 3 of $0.121 \pm 0.033$ mJy) instead of the expected $0.232$ mJy for $f_{\text{nth}} = 1$, averaged over all $N$ Green Peas using Equation (1) for a standard starburst template. The only other significant detection, in the mean image, is due to the unrelated FIRST J133926.7+151655. This indicates that the average radio fluxes of Green Peas are systematically suppressed, compared to usual starburst galaxies, by a factor of $f_{\text{nth}} \approx 0.53$. Thus, as in LBGs (Carilli et al. 2008), Green Peas have a comparable but systematically lower flux when compared to local starbursts.

4. GMRT OBSERVATIONS AND RESULTS

We targeted the three most promising candidates, with expected fluxes at the mJy level, using deep GMRT observations. We detect two of them as unresolved point sources at the $\sim 1$ mJy level and put an upper limit on the third. These results show that not all Green Peas may be characterized by a single $f_{\text{nth}}$. Observations with $\sim 3$ hr of on-source time for each Green Pea were carried out at 617 MHz (bandwidth 32 MHz, split into 512 channels). Visibility data have been analyzed using the Astronomical Image Processing System (AIPS; Greisen 1990).

Initial calibrations of the data were done using various flux calibrators and phase calibrators (see Table 1). The flux calibrators were observed at the beginning and the end of the respective observations in order to fix the antenna gains. The phase calibrators, chosen within $15^\circ$ of the source position on the sky, were observed every half an hour to calibrate the phase drift due to ionospheric effects. The data were binned into seven channels to maximize $S/N$ without compromising on chromatic aberration. Target visibilities were extracted from gain and bandpass calibrated data. The task IMAGR was used on this data to obtain a preliminary dirty map. Cleaning was done to remove the beam pattern for all $3\sigma$ and brighter sources. The source flux was then extracted with the task JMFIT from the final map, with a typical resolution of $\sim 6''$.

5. CHARACTERISTIC TIMESCALES IN GREEN PEAS

5.1. Electron Diffusion

Relativistic electrons produce bulk of the GHz radio emission in star-forming galaxies. They must remain confined long enough in the galaxy’s magnetic field to significantly contribute to the radio emission. We use the criteria derived here, to constrain the characteristic magnetic fields in Section 6.1. These electrons traveling at speeds close to that of light get scattered by the galaxy’s magnetic field. Their diffusion coefficient is determined by the structure of the magnetic field. We assume following Ginzburg & Syrovatski (1964) that the field structure is comprised of domains of radius $l_b$ (typically 0.3 kpc according to Calvez et al. 2010) with a randomly oriented magnetic field $B$ in each of these domains. For the range of feasible electron energies, the Larmor radius is smaller than the magnetic coherence length, thereby providing an energy-independent diffusion coefficient $D = l_b^2/3$. Therefore, the diffusion timescale for relativistic electrons to escape from a typical Green Pea of size 3 kpc (Cardamone et al. 2009) is

$$t_D \approx \frac{R^2}{D} \approx 2.94 \times 10^5 \text{ yr} \left(\frac{R}{3 \text{ kpc}}\right)^2 \left(\frac{l_b}{0.3 \text{ kpc}}\right)^{-1}. \quad (2)$$

This can be compared to the timescales of radiative processes to gauge their relative importance.
5.2. Inverse Compton Scattering

Electrons may lose their energy before diffusing out of a galaxy via Inverse Compton (IC) scattering. An explanation of the systematically lower fluxes of the LBGs suggested by Carilli et al. (2008) is IC cooling of relativistic electrons scattering off cosmic microwave background (CMB) photons. If this is indeed the cause, the effect should be negligible for Green Peas as the CMB radiation density in the universe has fallen off considerably in the epoch between LBGs (z ~ 2–5) and Green Peas (z ~ 0.2). Electrons can lose their energy through IC. IC has the same dependence on the photon energy density as synchrotron has on the magnetic field energy density (Rybicki & Lightman 1979). This implies the IC energy loss timescale:

\[
\tau_{IC} = \frac{E}{|dE/dt|_{IC}} \\
\simeq 1.29 \times 10^8 \text{ yr} \left( \frac{U_{rad}}{10^{-12} \text{ erg cm}^{-3}} \right)^{-3/4} \left( \frac{V_{syn}}{\text{GHz}} \right)^{-1/2},
\]

where \( U_{rad} \) is the energy density in radiation or photons.
For IC losses to be significant, $t_{IC}$ has to be comparable to $t_D$. This condition gives the required $U_{rad}$ as

$$U_{rad} \simeq 3.33 \times 10^{-9} \text{ erg cm}^{-3} \left( \frac{R}{3 \text{ kpc}} \right)^{-8/3} \times \left( \frac{l_0}{0.3 \text{ kpc}} \right)^{4/3} \left( \frac{v_{\text{syn}}}{\text{GHz}} \right)^{-2/3}. \quad (4)$$

The energy density of the CMB photons is given by

$$U_{\text{CMB}} \equiv aT^4 \simeq 4 \times 10^{-13} (1 + z)^4 \text{ erg cm}^{-3}. \quad (5)$$

This gives the timescale for IC losses against CMB photons as

$$t_{\text{CMB}} = \frac{E}{|dE/dt|_{\text{IC}}} \simeq 2.55 \times 10^8 \text{ yr} (1 + z)^{-3} \left( \frac{v_{\text{syn}}}{\text{GHz}} \right)^{-1/2}. \quad (6)$$

Comparing this to $t_D$, we get the redshift, at which the electrons lose a significant fraction of their energy to CMB photons, as

$$1 + z \simeq 9.54 \times \left( \frac{R}{3 \text{ kpc}} \right)^{-2/3} \left( \frac{l_0}{0.3 \text{ kpc}} \right)^{1/3} \times \left( \frac{v_{\text{syn}}}{\text{GHz}} \right)^{-1/6}. \quad (7)$$

This may be a significant effect for very high redshift ($z \sim 8.5$) galaxies. Thus, CMB IC cooling of relativistic electrons may have a role in explaining the systematic lowering of LBG radio fluxes. However, it cannot have any significant role in the case of Green Peas which are at $z \sim 0.2$.

Condon et al. (1991) suggested that radio emission from compact starbursts in ultraluminous infrared galaxies may be suppressed due to IC losses against the radiation energy density produced by its own young stellar population. Comparing the IC loss timescale to the electron diffusion timescale, we have obtained the required energy density in Equation (4). The typical value of $U_{rad}$, required for IC losses to significantly suppress the synchrotron flux at GHz frequencies, is much larger than the Milky Way value (Condon 1992) of $10^{-12}$ erg cm$^{-3}$ but less than the higher values of up to $10^{-8}$ erg cm$^{-3}$ which are seen by Condon et al. (1991) in compact starbursts. So, it is possible that some Green Peas may have suppressed radio fluxes as a result of IC losses against their own radiation density leading to a wide range of observed values for $f_{\text{inh}}$.

One out of three Green Peas observed by GMRT showed no detectable flux (Table 1). We therefore estimate $U_{rad}$ in this galaxy from its SDSS spectra, applying appropriate bolometric correction for a starburst galaxy. We find a $U_{rad} \approx 4 \times 10^{-12}$ erg cm$^{-3}$ which rules out IC cooling of electrons as the cause for suppression of radio luminosity. Hence, the upper limit of the flux from this object allows us to limit the magnetic field using the diffusion and equipartition arguments.

6. MAGNETIC FIELDS IN GREEN PEAS

6.1. Diffusion Argument

To explain the observed radio emission from Green Peas as synchrotron loss from electrons, the magnetic field must be large so that electrons lose enough energy before they diffuse out. This can be used to constrain magnetic fields in Green Peas. Since CMB IC cannot account for the systematic lowering of Green Pea radio fluxes we explore another explanation suggested by Carilli et al. (2008) for the suppression of LBG fluxes. Cosmic rays may diffuse easily from systematically smaller galaxies in the early universe before they can lose their energy via synchrotron emission. Since Green Peas are of sizes comparable to LBGs (Cardamone et al. 2009) this effect should be observable in Green Peas. Here, we use the observed radio emission to derive the magnetic field of a Green Pea by comparing the electron diffusion (Ginzburg & Syrovatskii 1964) and synchrotron energy loss timescales (Rybicki & Lightman 1979). Thus, we get a magnetic field required to explain the observed radio flux:

$$B_D \simeq 39 \mu G \left( \frac{R}{3 \text{ kpc}} \right)^{-4/3} \left( \frac{l_0}{0.3 \text{ kpc}} \right)^{2/3} \times \left( \frac{v_{\text{syn}}}{\text{GHz}} \right)^{-1/3} \left( \frac{f_{\text{inh}}}{0.5} \right)^{2/3}, \quad (8)$$

where the magnetic coherence length $l_0$ has a typical value of 0.3 kpc (Calvez et al. 2010). Using $f_{\text{inh}} \simeq 0.53$ at $v_{\text{syn}} = 1.4$ GHz (from the stacking experiment) and characteristic size (Cardamone et al. 2009) $R$ of 3 kpc, we obtain a typical magnetic field of $B \approx 36 \mu G$. Thus, the electron diffusion argument provides us with a direct estimate of the characteristic magnetic field in Green Peas.

6.2. Equipartition Argument

We show here that the previous estimate of magnetic field does not lead to absurd energy requirements. An independent estimate of magnetic field can be obtained from energy minimization considerations. The so-called equipartition magnetic field can be estimated by minimizing total energy invoked in relativistic particles and magnetic fields, in order to explain the observed flux. The magnetic field corresponding to the minimum energy condition of Burbidge (1956) in a synchrotron plasma can be derived from radio observations. We follow the derivation of Fitt & Alexander (1993) with the typical value of the cosmic-ray proton/electron energy ratio (Ginzburg & Syrovatskii 1964) $k = 100$ or alternatively the currently unknown number density ratio (Beck & Krause 2005); and a typical spectral index of $\alpha = 3/4$ (Fitt & Alexander 1993) for the radio spectrum, to derive the equipartition magnetic field as

$$B_{\text{eq}} \simeq 49 \mu G \left( \frac{S_v}{\text{mJy}} \right)^{2/7} \left( \frac{\theta}{1''} \right)^{-4/7} \left( \frac{v_{\text{syn}}}{\text{GHz}} \right)^{3/14}. \quad (9)$$

If the actual magnetic field is different from this value, the energy required to explain the synchrotron emission goes up very rapidly. It has been argued by Duric (1990) that the real magnetic field is limited to differ at most by an order of magnitude above and below the equipartition value derived in this manner. From the stacking experiment the mean flux of the Green Peas is $S_v \sim 0.12$ mJy. While they are unresolved at VLA FIRST resolution, serendipitous HST observations (Cardamone et al. 2009) provide their characteristic size as 3 kpc (where 1'' is ~5 kpc at their typical redshift).

This fixes the characteristic equipartition magnetic field of Green Peas at $B \approx 39 \mu G$. The surprising agreement between the estimates of Green Pea magnetic fields derived from two independent methods points to a characteristic magnetic field of $\geq 30 \mu G$ which is comparable to or even larger than the average Milky Way value of $B \approx 5 \mu G$ (Condon 1992).
7. DISCUSSION

We report the first radio detection of Green Peas and show that it implies large (\(\sim 30\mu G\)) magnetic fields in them. Given that the bulk of stars in Green Peas have formed in the past \(\sim 10^8\) years as deduced from modeling of integrated spectra (see Figure 1), the discovery of radio emission and the implied \(\mu G\) magnetic fields is a striking result. Any old component, if present, in the Green Peas would contribute very little energy injection from star formation activity and will not be able to amplify the field. Present day magnetic fields are thought to be the result of amplification of seed fields (\(\sim 10^{-20}\) to \(10^{-18}\) G) by dynamo action (Widrow 2002), which transfers turbulent kinetic energy to magnetic field energy, over the galaxy’s lifetime. These models for the growth of galaxy scale magnetic fields have \(e\)-folding times (Widrow 2002) of \(\approx 10^8\) to \(10^9\) yr. They produce 20 (Kulsrud & Zwiebel 2008) to 50 (Rees 2006) \(e\)-folds of an efficient dynamo during the lifetime of the Milky Way. Hence, they can only play a small role in amplifying the pregalactic (Kulsrud & Zwiebel 2008) magnetic fields within the age of a Green Pea. Small-scale magnetic fields may be efficiently amplified by fluctuation dynamos, on eddy turn over timescales (of around \(\sim 10^7\) years in the Milky Way) (Blackman 1998; Brandenburg & Subramanian 2005). The clumpy appearance of Green Peas in HST images may imply small-scale turbulence. Upcoming VLA polarization observations of Green Peas by the authors will test the contribution of small-scale fields. Daly & Loeb (1990) suggest that galaxy-wide \(\mu G\) level magnetic fields may be generated by magnetized plasma produced in jets from a central compact object. This is unlikely as we are considering only star-forming Peas and not Seyfert Peas. Our results strongly favor the suggestion from Kulsrud & Zwiebel (2008) that seed fields were amplified significantly by turbulence (up to \(\mu G\) level pregalactic fields) as protogalaxies and similar substructures formed.

As Green Peas are close analogs to LBGs it seems likely that young primeval galaxies could have had strong enough magnetic fields to seed the intergalactic magnetic field (Kronberg et al. 1999). It has been suggested by Zeldovich et al. (1983) that magnetic fields may play a crucial role in star formation by assisting the infall of ionized gas. Observed magnetic fields in nearby galaxies scale slowly with the SFR (Vallee 1994) but it is likely that magnetic fields increase star formation efficiency (Totani 1999). In such a scenario, presence of strong pregalactic magnetic fields may be the reason why Green Peas have started to produce stars at such a high rate. Most theoretical and computational studies of reionization era assume lack of dynamically significant magnetic fields (Loeb & Barkana 2001), during formation of first stars. Our results may require a rethinking of this assumption, in presence of \(\mu G\) level pregalactic magnetic fields. A detailed study of processes at work in Green Peas in the nearby universe will help us understand magnetic field amplification in early galaxies, and its role in star formation, supernova feedback, and cosmic-ray acceleration.

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