Cosmic Ray Interactions in Starburst Galaxies

Stephen K N PORTILLO

Introduction

Cosmic Rays in Context

Cosmic rays are relativistic charged particles seen with energies from ~10^6 eV to 10^{20} eV. Most (~90%) cosmic rays are protons, while ~10% are helium nuclei, a further ~1% are heavier nuclei, ~1% are free electrons, and even smaller numbers are positrons and antiprotons. When cosmic ray protons and nuclei interact with the Earth's atmosphere, they create showers of secondary particles that are detectable by ground-based and airborne instruments. Cosmic rays are also detected by instruments in orbit, but their spectrum below ~GeV is uncertain because the Sun's magnetic field significantly deflect these particles as they approach the Solar System.

The local energy density of cosmic rays (~1 eV cm^{-3}) is comparable to the energy density of visible starlight (~0.3 eV cm^{-3}), and the galactic magnetic field (~0.25 eV cm^{-3}), suggestive of their capacity to be a major influence on galactic dynamics. Cosmic rays undergo inelastic collisions with the gas they traverse, contributing to the gas's ionization and heating. It is the cosmic rays with energies ~GeV that are most effective at ionizing; combined with the uncertainty of the cosmic ray spectrum at this energy because of the Sun's magnetic field, thus even the local cosmic ray ionization rate is uncertain. As charged particles, cosmic rays are force to gyrate about magnetic field lines as they move. This gyration can excite resonant Alfvén waves in the magnetic field, which in turn affects how the cosmic rays propagate. The interplay between the magnetic field and cosmic rays depends heavily on the properties of the magnetic field (Aharonian, et al., 2012).

Supernova remnants are major sources of cosmic rays through the process of first order Fermi acceleration (Bell, 1978). The energy density of cosmic rays can be explained if ~10% of the bulk kinetic energy of supernovae is used in accelerating cosmic rays. The outward propagating supernova shock creates turbulence behind it (downstream). Charged particles can scatter off the turbulent magnetic field downstream, gaining some energy and moving into the region in front of the shock (upstream). These energetic charged particles excite Alfvén waves upstream, and these Alfvén waves scatter the particles back downstream. This process repeats, giving the particles more and more energy until they can escape. This acceleration mechanism predicts a power law spectrum of power 2 to 2.5 as well as a deficit of electrons, agreeing well with the observed spectrum. In supernova remnants, synchrotron radio emission established the acceleration of electrons (Drury, et al., 2001), and gamma-ray emission in nearby molecular clouds further points to the acceleration of cosmic rays (HESS Collaboration, 2007). Being sourced by supernova remnants would intimately link cosmic rays with star formation, making cosmic rays a possible feedback mechanism in galactic evolution.

Cosmic Ray Interactions in Starburst Galaxies

Thus, cosmic rays should have the largest role to play in the evolution of starburst galaxies, which contain the most vigorous star forming environments observed. Starburst galaxies contain compact regions with much higher star formation rates than typically expected. It is thought that starbursts are the product of galaxy mergers: tidal forces draw the gas to the center of the galaxy, compressing the gas and causing vigorous star formation. With the increased supernova rate, cosmic ray densities of ~100 times the local cosmic ray density can be seen in the largest starbursts.

This work will focus on two manifestations of cosmic ray interactions in starburst galaxies: the far infrared-radio correlation and cosmic ray dominated regions. The far IR-radio correlation shows a relation between cosmic ray density and star formation rate, but also constrains where and how cosmic rays lose their energy to the galaxy's interstellar medium. Foremost, this correlation shows that the cosmic ray density increases with star formation density. This correlation also supports the idea that cosmic rays lose a significant amount of energy in ionizing the molecular gas, leading to arguments in support of cosmic ray dominated regions in starbursts. Dense cores in molecular clouds are opaque to UV starlight, meaning cosmic rays are likely the dominant ionization and heating source. In starbursts, the enhanced cosmic ray density increases the temperature and ionization of these dense cores, changing the initial conditions for star formation inside them, thus changing star formation on a galactic scale.

Thus, this work will focus on how cosmic rays directly contribute to the heating and ionization of molecular gas, while ignoring other important cosmic ray interactions. For example, via the streaming instability, cosmic rays amplify turbulence in the magnetic field, increasing the magnetic field's energy density (Zweibel, 2003). Also, cosmic rays scatter off the Alfvén waves they excite, contributing to the gas pressure, and possibly contributing to galactic winds (Breitschwerdt, et al., 1991). These Alfvén waves also contribute to the heating of the gas when they are damped (Wentzel, 1971).

Radio-Far Infrared Correlation

Electron Calorimetry

The radio-far infrared correlation is an empirical relation seen in star forming galaxies from local dwarfs to the largest starbursts, showing a linear relation between the far infrared emission and the GHz radio emission (Bell, 2003). The far infrared emission is the ultraviolet light from massive stars absorbed and remitted by dust, while the GHz radio emission is synchrotron emission from cosmic ray electrons interacting with the galaxy's magnetic field. This relation also holds at sub-kiloparsec scales within galaxies. The tightness of this relation allows us to learn about the many interactions of cosmic rays with different components of the galaxy.

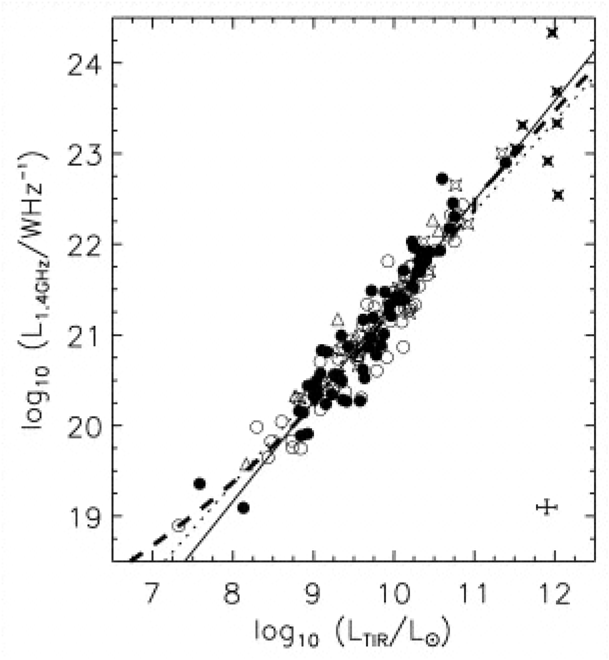

Figure 1. Radio- IR correlation for 162 galaxies. Reprinted from (Bell, 2003).

The simplest picture of the radio-far infrared correlation is "electron calorimetry" (Voelk, 1989), where cosmic rays electrons lose a constant fraction of their energy to synchrotron.

The star formation rate is proportional to the number of massive stars alive and the supernova rate. The massive stars emit ultraviolet, which is then reprocessed by dust into infrared. Then, a constant fraction of the supernova energy goes into accelerating cosmic rays. If the synchrotron cooling time is shorter than the time it takes for the cosmic ray electron to escape the galaxy by diffusion or advection, and shorter than the cooling time by other processes, then cosmic ray electrons lose all their energy to synchrotron emission. With the number of massive stars determining how much infrared light is seen, and the supernova rate determining the synchrotron emission, a linear relation between infrared and synchrotron emission is predicted. If ~0.2% of supernova kinetic energy goes into a power law spectrum of electrons 2 to 2.4, then the scale of the radio-far infrared correlation is recovered.

The radio-far infrared correlation holds for galaxies over six decades of starlight energy density, constraining the magnetic field in terms of the starlight energy density. However, with a greater starlight density comes a greater chance that cosmic ray electrons will upscatter photons via inverse Compton. Recall that the synchrotron power and inverse Compton power for a single electron have very similar forms:

$$P_{IC} = \frac{4}{3}\sigma_T c\beta^2\gamma^2 U_{ph}$$
$$P_{synch} = \frac{4}{3}\sigma_T c\beta^2\gamma^2 U_B$$

Electron calorimetry relies on synchrotron emission being the dominant energy loss mechanism for electrons, or at least a constant fraction of electron energy loss. The electrons in larger galaxies with greater starlight density would be expected to lose more energy to inverse Compton, threatening to rival and overpower synchrotron losses over the great range of the far infrared-radio correlation. However, if $U_B \sim U_{ph}$ is somehow maintained, then synchrotron remains an important cooling process and electron calorimetry is maintained (Lisenfeld, et al., 1996). Locally, it is known that the magnetic field energy density is comparable to that of starlight, so it is reasonable that other galaxies could satisfy this condition. The mechanism that brings about this equipartition is unclear, but it is thought that magnetic fields are amplified to be in equipartition with turbulent energy (Stone, et al., 1998). Star formation activity provides both starlight energy and turbulent energy, explaining the rough equality.

The Spectral Index Problem

So far, electron calorimetry assumes that synchrotron and inverse Compton are the dominant energy loss mechanisms, which predicts the GHz radio spectral index. First-order Fermi acceleration in supernova shocks predict that cosmic ray electrons are injected with a spectrum of index 2 to 2.5. The rate of energy loss of electrons to both synchrotron and inverse Compton is sharply energy dependent $\propto \gamma^2$, leading to a steep equilibrium electron energy spectrum. From electrons cooled by synchrotron and inverse Compton, a synctrotron spectral index of 1 to 1.2 is expected, which is steeper than is seen in star forming galaxies (Clemens, et al., 2008). Further cooling mechanisms that can flatten the electron spectrum would bring the predicted radio spectrum back into agreement with observation. Bremsstrahlung and ionization losses have a shallower energy dependence ($\propto \gamma^1, \gamma^0$ respectively), leading to a shallower electron spectrum and thus shallower synchrotron spectral index. For this solution to work, either bremsstrahlung or ionization energy losses must be comparable to the synchrotron and inverse Compton losses. The densest galaxies have the shallowest synchrotron spectra and bremsstrahlung and ionization losses increase with density ($t \propto n^{-1}$), supporting this solution.

The importance of bremsstrahlung and/or ionization relative to synchrotron and inverse Compton must be maintained for galaxies across the range of the far infrared-radio correlation. From electron calorimetry, we have the prediction $U_B \sim U_{ph}$, and from the Kennicutt-Schmidt law, we have $\Sigma_{SFR} \propto \Sigma_{gas}^{1.4}$. These two relations allow us to relate the magnetic field ($B^2 \propto U_B$) and the gas density, via $U_{ph} \propto \Sigma_{SFR}$, yielding $B \propto \Sigma_{gas}^{0.7}$. With this magnetic field scaling, the scaling of the synchrotron cooling time compared with the bremsstrahlung and ionization cooling time as a function of density can be found:

$$t_{synch}/t_{ion} \propto n^{3/10}$$
$$t_{synch}/t_{brem} \propto n^{-1/20}$$

So ionization losses become more important in denser galaxies, but won't grow to overwhelm synchrotron losses, allowing ionization to explain the observed shallow radio spectral index (Thompson, et al., 2006). The bremsstrahlung time scale scales almost exactly with the synchrotron time scale, meaning the relative importance of synchrotron and bremsstrahlung stays the same with density in galaxies that obey electron calorimetry. But modelling finds that bremsstrahlung losses are faster than synchrotron losses in starburst galaxies by a factor of 10, implying that synchrotron is always subdominant, endangering electron calorimetry. Starburst galaxies would be expected to be radio deficient compared to the far infrared-radio correlation, as a large amount of cosmic ray energy would be lost to bremsstrahlung instead of synchrotron.

Proton Calorimetry and Other Solutions

The far infrared-radio correlation can be maintained with a process that increases synchrotron emission at the same rate that bremsstrahlung energy losses occur, such as “proton calorimetry” (Lacki, et al., 2010). Cosmic ray protons interact with nuclei in gas with timescale $t \propto n^{-1}$, creating neutral and charged pions that then decay into products including secondary electrons (and positrons). These secondary electrons then increase the amount of synchrotron emission that can be seen. Supernova remnants accelerate many more cosmic ray protons than electrons, and so they carry more energy than the electrons, about 10% of the supernova kinetic energy. Synchrotron losses are subdominant to bremsstrahlung, but pion creation provides secondary electrons that emit synchrotron along with the primary electrons directly from supernovae. Since pion creation and bremsstrahlung have the same rate dependence on the gas density, the synchrotron contribution from the secondary electrons grows with the bremsstrahlung losses. The ratio of the energy that supernova shocks produce in cosmic ray protons versus cosmic ray electrons is just right: as bremsstrahlung losses become more important and take energy away from primary electrons, pion creation adds enough secondary electrons to maintain the same synchrotron emission.

Said another way, from combining the relation $U_B \sim U_{ph}$, which kept synchrotron comparable to inverse Compton, and the Kennicutt-Schmidt law, the relation $B \propto \Sigma_{gas}^{0.7}$ between magnetic field density and gas is found. This relation then keeps the bremsstrahlung cooling time a constant fraction $(\frac{1}{10})$ of the synchrotron cooling time. Pion creation and bremsstrahlung losses both occur on time scales $\propto n^{-1}$, and the ratio of cosmic ray protons to cosmic ray electrons means that secondary electrons from pion decay are created in the right proportion to create synchrotron to compensate for the bremsstrahlung losses, which is possible because the synchrotron and bremsstrahlung time scales stay in the same proportion.

Dropping the assumption of electron calorimetry, galactic winds are another possible solution to the spectral index problem (Lisenfeld, et al., 1996). If cosmic rays are advected quickly by the wind, then the other energy loss mechanisms will not sharpen their spectrum, giving a shallower synchrotron spectrum. However, in large starbursts, the wind speeds required to compete with inverse Compton are larger than those observed; however, in M82, these wind speeds may be achieved. Also, this scenario would require the cosmic ray electron injection rate per supernova to increase with the strength of the galactic wind, a strange connection. If 10% of supernova kinetic energy goes into cosmic ray protons, 40% of proton energy must go into pionic losses to explain M82's gamma ray luminosity, which means advection cannot be dominant. Gamma ray detections of more starburst galaxies would strengthen this argument (Thompson & Lacki, 2013).

Instead of significant bremsstrahlung cooling of cosmic ray electrons, thermal bremsstrahlung emission (from thermal gas rather than relativistic particles) from HII regions could explain the shallow GHz radio spectrum. However, looking at even higher frequencies of 30 GHz, the spectrum is far too sharp to be dominated by thermal bremsstrahlung. Thermal bremsstrahlung is constrained to contribute only 10% of the GHz radio emission. If cosmic ray electrons emit synchrotron while in HII regions, thermal bremsstrahlung absorption by the ionized gas can be seen at frequencies below 1 GHz.

(Condon, et al., 1991)Such absorption is seen in M82, but the remaining strength of synchrotron emission suggests that cosmic ray electrons lose much of their energy outside HII regions (Lacki, 2013).

Gamma Rays from Proton Calorimetry

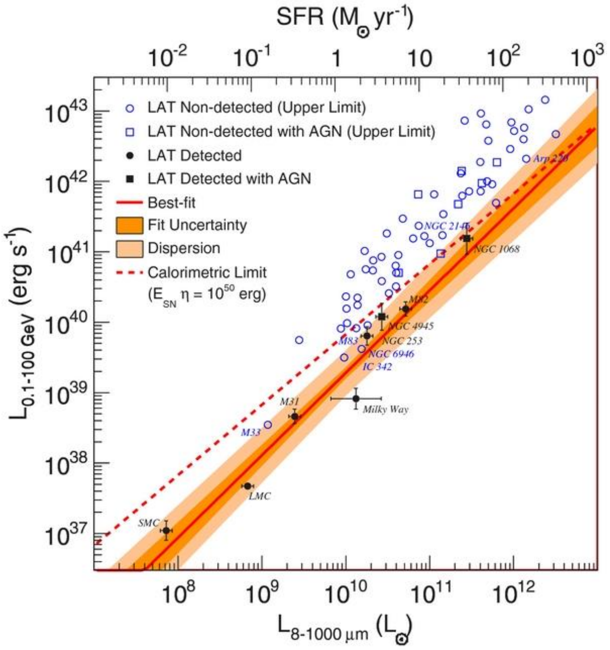

Figure 2. Gamma-ray luminosity vs. total IR luminosity for star forming galaxies. Reprinted from (Fermi Collaboration, 2012).

If proton calorimetry saves the bremsstrahlung/ionization explanation of star forming galaxies' radio spectral indices, then we should see the other products of pion decay, including gamma rays. If cosmic ray proton energy is all lost to pion decay, or at least a constant fraction of it is, then a linear far infrared-gamma ray correlation is expected. For a constant fraction of proton energy to go into pion creation, protons cannot escape the galaxy on time scales faster than the pion creation time scale. Measurements from Fermi are consistent with an infrared-gamma ray correlation, supporting this scenario (Fermi Collaboration, 2012). The pionic losses are seen in the gamma ray spectrum, allowing the cosmic ray proton energy density to be estimated. Comparing with the synchrotron radiation expected from the secondary electrons these protons create, it can be seen that cosmic ray electrons suffer bremsstrahlung and ionization losses that reduce the synchrotron they emit. Thus, both cosmic ray electrons and protons lose a significant fraction of their energy in heating and ionizing the gas in star forming galaxies, and especially in starburst galaxies.

Better constraints on the gamma ray emission of starburst galaxies below 1 GeV would actually constrain the inverse Compton emission, bremsstrahlung emission, and pionic emission. Inverse Compton could be confirmed to be of the same importance as synchrotron, allowing electron calorimetry. Bremsstrahlung from cosmic ray electrons could be seen without confusion with thermal bremsstrahlung, confirming bremsstrahlung as the solution to the spectral index problem. Finally, it can be confirmed that the pionic emission is strong enough to counter the losses from bremsstrahlung, allowing proton calorimetry to maintain the far infrared-radio correlation.

Cosmic Ray Dominated Regions

Dense Cores as Cosmic Ray Dominated Regions

The idea of proton calorimetry invoked to explain the spectral index problem of the far infrared-radio correlation implies that cosmic ray protons are interacting with the gas in galaxies. In particular, they must be interacting with the dense gas in order to lose such a large fraction of their energy to pionic losses. The cosmic ray energy losses will contribute to the ionization and heating of this dense gas.

Ultraviolet radiation dictates the state of much of the interstellar medium in normal star forming galaxies, so much of the medium may be deemed a “photon dominated region.” Ultraviolet radiation easily ionizes atoms and dissociates molecules, and is readily absorbed by dust grains. These interactions drive the heating, ionization, and chemistry of the phases of the interstellar medium. Only the very densest regions of molecular clouds are shielded from ultraviolet radiation, comprising 1-5% of molecular gas mass.

Since they do not interact with gas as strongly as ultraviolet light, cosmic rays can reach these denser regions and affect their state – making these regions possible “cosmic ray dominated regions.” In normal star forming galaxies, cosmic rays ionize the gas to $\sim 10^{-8}$. At these densities, supersonic turbulence has already been dissipated (Pineda, et al., 2010), and thus does not heat the gas. The dust is heated by infrared that can penetrate the dense gas, while the gas is heated by cosmic rays. The rate of dust-gas collisions at these high densities couples the temperatures of the gas and dust, to ~10 K. These conditions are seen in the Milky Way (Bergin & Tafalla, 2007).

The conditions in cosmic ray dominated regions are remarkably uniform, possibly explaining the universality of the initial mass function of star formation (Elmegreen, et al., 2008). A boost of the cosmic ray rate by 10 times still yields a low ionization. Magnetic fields can only thread through molecular gas when it is partially ionized, and low ionization is essential for ambipolar diffusion to remove this magnetic support. The dense gas has little turbulence and is coupled to the dust temperature, which is determined by the infrared which pervades the galaxy. These mechanisms mean cosmic ray dominated regions across the galaxy have similar turbulent and thermal states, and similar Jeans’ masses. Cosmic ray dominated regions, being the densest parts of molecular clouds are the dense cores which collapse to form stars. Thus, the effects of cosmic rays in these regions determine the initial conditions of star formation.

Cosmic Ray Dominated Regions in Starburst Galaxies

In ULIRGs, the most compact starbursts, cosmic ray dominated regions come to dominate the molecular gas. The merger tidal torques that compress the molecular gas and the intense star formation that occurs creates high turbulent pressures and high gas density in these galaxies. More of the molecular gas is shielded from ultraviolet, leaving cosmic rays to interact with the gas. The high density of star formation creates a high cosmic ray density, ~1000 higher than in the Milky Way. (Papadopoulos, 2010) With high cosmic ray density and high density of the gas they interact with, much more heating and ionization occurs. This heating overwhelms the gas-dust coupling, driving the gas temperature higher to ~50-100 K, which is observed in NGC 253 (Bradford, et al., 2003). The ionization is increased to ~10^{-6}, and the chemistry present is changed (Bayet, et al., 2011).

These heating and ionization conditions change how star formation will occur in dense cores in ULIRGs. In gravoturbulent regulated star formation, turbulence creates overdensities that then collapse by gravity. The choice of density scale where the Jeans mass sets the characteristic mass of stars is still unclear, but the high temperatures increase the Jeans mass drastically at all densities. Within dense cores, the Jeans mass ranges from 3 to 10 solar masses, supressing low mass star formation. In ambipolar diffusion regulated star formation, the molecular gas decouples from the ionized gas which is supported by the magnetic field. The molecular gas slowly gravitationally collapses, occasionally hindered by colliding with ions. As the molecular gas diffuses away from the ionized gas, ion-neutral collisions happen less and less often, removing magnetic support and allowing collapse. The higher ionization changes the ambipolar diffusion timescale from ~Myr to ~Gyr. Another mechanism is needed to remove magnetic support fast enough to support the starburst star formation rate, such as magnetic reconnection diffusion. These changes caused by high cosmic ray density suggest that the initial mass function can be dependent on Σ_{SFR} – i.e. whether the galaxy is starbursting or not (Papadopoulos & Thi, 2013).

Other Heating Mechanisms

X-rays from AGN are also more penetrating than ultraviolet, also possibly heating the dense cores in starbursts that contain AGN. Similarly to the idea of cosmic ray dominated regions, it has been suggested that powerful AGN create X-ray dominated regions (Bradford, et al., 2009). Even if the molecular gas is X-ray dominated, the high gas densities and high cosmic ray densities in starburst galaxies means that cosmic rays still contribute to heating and ionization. Specific lines, like the high-J CO lines, can discriminate cosmic ray heating from photoionization heating (Hailey-Dunsheath, et al., 2008),and ALMA is well placed to conduct these observations on many galaxies.

Given that cosmic rays interact strongly enough with the molecular gas to lose much of their energy to pions, it is possible that even denser parts of molecular clouds are shielded from cosmic rays. Also, cosmic rays propagation may leave some molecular gas untouched. However, the gamma rays produced when protons undergo pionic losses are highly penetrating. Gamma rays will travel a column density ~200 g cm^{-2} before pair producing electrons. The power from these gamma rays is not enough to overcome the gas-dust coupling, and so does not raise the temperature, instead the gamma rays only contribute ionization (Lacki, 2013).

Conclusion

The role of cosmic rays in galactic dynamics is still an open question, but parts of the answer are coming into focus, especially in starburst galaxies. It is now known that supernova remnants produce a significant fraction of cosmic rays, expounding that cosmic ray production is associated with star formation activity. Then, from the most densely star forming galaxies, much can be learned about the interaction of cosmic rays with their galaxies.

Interpreting the observed far infrared-radio correlation in star forming galaxies not only links cosmic rays and star formation, but also determines how cosmic ray electrons and protons interact in the galaxy. To explain the synchrotron radio emission in the face of larger inverse Compton losses from starlight in the densest starbursts, some mechanism must drive magnetic fields into rough equipartition with starlight. Then, the shallow radio spectral indices seen can be explained by strong bremsstrahlung or ionization losses. Finally, strong bremsstrahlung losses in the densest galaxies need not ruin the far infrared-radio correlation if proton calorimetry holds. Cosmic ray protons interacting with gas will produce secondary electrons that emit enough synchrotron to offset the bremsstrahlung losses. While current gamma ray spectra are consistent with proton calorimetry, further detections and studies will have the power to test and refine this story.

Proton calorimetry hints that cosmic rays are a major influence on the thermal and ionization state of the dense star forming gas in starbursts. Dense cores in molecular clouds are cosmic ray dominated regions – regions that are shielded from ultraviolet, and whose state is instead governed by cosmic rays. In starburst galaxies, the high pressures from intense star formation activity increase the density of molecular clouds. Combined with a higher cosmic ray density, also from the galaxy's star formation, the dense gas can be drastically affected. Pionic losses from cosmic ray protons can heat the gas, raising the Jeans' mass, and ionize the gas, slowing ambipolar diffusion. These changes in the initial conditions of star formation will likely change the initial mass functions of starbursting galaxies. Cosmic ray interactions with molecular gas are discernable through chemical signatures, which will soon be observable in many ULIRGs.

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