Relating Diffusion Properties of Cosmic-Ray Electrons to Star Formation Activity within Normal Galaxies

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Abstract. Using data obtained as part of the Spitzer Infrared Nearby Galaxies Survey (SINGS, Kennicutt et al. 2003) and WSRT-SINGS radio continuum survey (Braun et al. 2006), we study the effects of star-formation activity on the far-infrared (FIR)–radio correlation within galaxies. This is done by testing a phenomenological model for the correlation, which describes the radio image as a smeared version of the FIR image. We find that this description works particularly well for galaxies with higher infrared surface brightnesses, yielding best-fit smoothing scale-lengths of a few hundred parsecs, substantially shorter than those for lower surface brightness galaxies. We interpret this result to suggest that galaxies with higher disk averaged star formation rates have had a recent episode of enhanced star formation and are characterized by a higher fraction of young cosmic-ray (CR) electrons compared to galaxies with lower star formation activity.

Introduction

The relativistic phase of the interstellar medium (ISM) is a collision-less gas of diffusing cosmic-ray (CR) particles. While this phase is often overlooked in extragalactic studies of star formation, largely due to the difficulties involved with making direct observations of CR nuclei, it has an energy density comparable to the gaseous phases proving it to be equally important in studies of galaxy evolution. The distances diffused by CRs within galaxies depends on their age and effective mean free path. Consequently, pinning down these scale-lengths can provide rough estimates for the ages of related star formation episodes as well as help to constrain associated ISM parameters.

Synchrotron emission from normal galaxies is readily observable at radio wavelengths and directly probes the coupling between a galaxy’s distribution of CR electrons and its magnetic field. However, these data alone do not provide information on the propagation history of CR electrons. The close spatial correlation between the far-infrared (FIR) and predominantly non-thermal radio continuum (RC) emission of normal late-type galaxies suggests a common physical origin, most likely through the processes of massive star formation (e.g. Murphy et al. 2006a, and references therein). Massive stars are thought to be the primary heating sources of dust and whose remnants accelerate CR electrons in galaxies. Since CR electrons diffuse measurably farther (∼1 kpc) than the mean free path of dust-heating photons (∼100 pc), a galaxy’s radio image should appear as a smoother version of its FIR map which can be related by the diffusion history of its CR electrons (Bicay & Helou 1990).
Using this phenomenology, we relate the spatial distributions of FIR (70 µm) and RC (22 cm) emission for 12 spiral galaxies by a smearing kernel which, when convolved with a galaxy’s 70 µm map, minimizes the residuals between the spatial distributions of the two maps. In Figure 1 we plot the best-fit smearing scale-length against each galaxy’s total-infrared (TIR; 3-1100 µm) surface brightness, which we express as star formation rate (SFR) surface density (ΣSFR). We find the general property that galaxies are better modeled by larger smearing scale-lengths if their disk-averaged SFR is lower. The complete study can be found in Murphy et al. (2006b).

**Discussion**

We interpret our results as an indication that CR electrons are, on average, closer to their place of origin in galaxies having higher star formation activity. We consider three general explanations for this result, whereby CR electrons in more active galaxies: (1) have shorter lifetimes due to a high energy loss rate; (2) diffuse more slowly due to a high ISM density and magnetic field strength; or (3) have been accelerated more recently and are younger on average. The first two of these explanations are compatible with steady-state star formation, while the third suggests a recent episode of enhanced star formation.

In Figure 1 we plot the expected relation between CR electron diffusion length and TIR surface brightness for the steady-state cases, taking into account the dependence of diffusion on the ISM parameters, and including Inverse Compton losses (dashed line) and then both Inverse Compton and synchrotron losses (solid line). For the latter, we assume that CR electrons diffuse according to an energy dependent diffusion coefficient which scales with ISM density and magnetic field strength, and plot the steepest scaling (see Murphy et al. 2006b, for details). The observed trend is is ∼9 and ∼2 times steeper than the simple models shown in Figure 1. We therefore conclude that galaxies with higher ΣSFR are likely to have experienced a recent episode of enhanced star formation compared to galaxies with lower disk-averaged SFRs, leading to a larger fraction of relatively young CR electrons within their disks.

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