SUPERNOVA-ENHANCED COSMIC-RAY IONIZATION AND INDUCED CHEMISTRY IN A MOLECULAR CLOUD OF W51C

C. Ceccarelli$^1$, P. Hily-Blant$^1$, T. Montmerle$^{1,2}$, G. Dubus$^1$, Y. Gallant$^3$, and A. Fiasson$^4$

$^1$ UJF-Grenoble 1/CNRS-INSU, Institut de Planétologie et d’Astrophysique de Grenoble (IPAG) UMR 5274, Grenoble, France; Cecilia.Ceccarelli@obs.ujf-grenoble.fr, Pierre.Hily-Blant@obs.ujf-grenoble.fr, Guillaume.Dubus@obs.ujf-grenoble.fr

$^2$ Institut d’Astrophysique de Paris, CNRS, France; montmerle@iap.fr

$^3$ Laboratoire de Physique Théorique et Astroparticules, UMR 5207, CNRS/IN2P3, Université Montpellier II, France; Yves.GALLANT@lpta.in2p3.fr

$^4$ LAPP, Laboratoire d’Annecy-le-Vieux de Physique des Particules, UMR IN2P3-CNRS, Université de Savoie, Annecy-le-Vieux, France; fiasson@lapp.in2p3.fr

Received 2011 June 12; accepted 2011 August 9; published 2011 September 16

ABSTRACT

Cosmic rays (CRs) pervade the Galaxy and are thought to be accelerated in supernova shocks. The interaction of CRs with dense interstellar matter has two important effects: (1) high-energy ($\gtrsim 1$ GeV) protons produce $\gamma$-rays by $\pi^0$-meson decay and (2) low-energy ($\lesssim 1$ GeV) CRs (protons and electrons) ionize the gas. We present here new observations toward a molecular cloud close to the W51C supernova remnant and associated with a recently discovered TeV $\gamma$-ray source. Our observations show that the cloud ionization degree is highly enhanced, implying a CR ionization rate $\sim 10^{-15}$ s$^{-1}$, i.e., 100 times larger than the standard value in molecular clouds. This is consistent with the idea that the cloud is irradiated by an enhanced flux of low-energy CRs. In addition, the observed high CR ionization rate leads to an instability in the chemistry of the cloud, which keeps the electron fraction high, $\sim 10^{-5}$, in a large fraction ($A_e \gtrsim 6$ mag) of the cloud and low, $\sim 10^{-7}$, in the interior. The two states have been predicted in the literature as high- and low-ionization phases (HIP and LIP). This is the observational evidence of their simultaneous presence in a cloud.

Key words: ISM: abundances – ISM: molecules

Online-only material: color figures

1. INTRODUCTION

Cosmic rays (CRs) pervade the Galaxy. In the dense interstellar medium, they play a crucial role as they are the primary source of ionization, starting a complex chemistry which leads to hundreds of molecules, and influencing the star and planet formation processes by creating ions, which in turn are coupled with the magnetic fields, thus regulating gravitational collapse.

There is little doubt that CRs are accelerated in the expanding shocks of supernova remnants (SNRs; e.g., Hillas 2005; Caprioli et al. 2011). High-energy ($\gtrsim 1$ GeV) CRs (mainly protons) interact with hydrogen atoms and produce $\gamma$ rays via $\pi^0$ decay (Hayakawa 1952; Stecker 1971). In this case, the predicted $\gamma$-ray luminosity $L_\gamma$ is proportional to the $\pi^0$-decay $\gamma$-ray emissivity, which depends on the local CR density, and to the irradiated molecular cloud mass (e.g., Aharonian & Atoyan 1996). Hence, giant molecular clouds close to, or even better, penetrated by SNRs can be bright $\gamma$-ray sources. Conversely, molecular clouds associated with bright $\gamma$-ray sources can probe enhanced CR densities. Several CR interaction sites have now been tentatively identified with the latest generation of GeV/TeV observatories (e.g., Montmerle 2010). The main difficulty remains in distinguishing between emission from proton and/or bremsstrahlung or inverse Compton from electrons. Even in well-documented cases such as IC443 (Albert et al. 2007) and W28 (Aharonian et al. 2008) SNRs, the GeV–TeV emission mechanism remains unclear. In other cases (in particular for W51C; Abdou et al. 2009; Feinstein et al. 2009) $\pi^0$-decay appears to be the dominant $\gamma$-ray emission mechanism. In these cases, the derived local relativistic proton density is very high, typically one to two orders of magnitude higher than the average galactic CR density. Such high densities should also have visible effects at lower CR energies ($\lesssim 1$ GeV), in the regime where CRs ionize molecular clouds (e.g., Kamae et al. 2006; Gabici et al. 2009; Padovani et al. 2009; Fatuzzo et al. 2010).

We propose that the physical interaction between SN-accelerated energetic particles and molecular gas, where an association is suggested by the presence of a $\gamma$-ray source, can be demonstrated by using the impact of low-energy CRs on the cloud chemistry. The method is based on the determination of the ionization degree of the molecular cloud, which in turn gives a measure of the CR ionization rate $\zeta$ (to be compared with the “standard” value $\zeta_0 \sim 10^{-17}$ s$^{-1}$ for dense clouds; Glassgold & Langer 1974). In dense gas, the ionization can be obtained by measurements of the DCO$^+$/HCO$^+$ abundance ratio (e.g., Güélin et al. 1977). Briefly, HCO$^+$ and DCO$^+$ are formed by the reaction of CO with H$^+$ and H$_2$D$^+$, respectively: CO + H$^+$ → HCO$^+$ + H and CO + H$_2$D$^+$ → DCO$^+$ + H$_2$. Consequently, the DCO$^+$/HCO$^+$ ratio directly depends on H$_2$D$^+$/H$_3^+$ only. In molecular clouds, CRs ionize the gas by ionizing H and H$_2$ at a rate $\zeta$ and forming the molecular ion H$^+_3$, whereas H$_2$D$^+$ is formed by the reaction of H$_3^+$ with HD. Since both molecules are destroyed by the reaction with the most abundant neutral species, CO, and by the recombination with electrons, the DCO$^+$/HCO$^+$ ratio is an almost direct measure of the gas ionization degree. The method has been extensively applied to derive the ionization degree of molecular clouds and dense cores. The measured values range between $1 \times 10^{-8}$ and $1 \times 10^{-6}$, depending on the gas density, leading to estimates of $\zeta$ between $10^{-18}$ and $10^{-16}$ s$^{-1}$ (Caselli et al. 1998, hereinafter CWTH98). Finally, Indriolo et al. (2010) recently reported line absorption observations of H$^+_3$, measuring the ionization in the diffuse gas of the
outer parts of the cloud associated with IC443. Their measurements indicate values of $\xi$ only five times larger than the average in diffuse clouds. In this Letter, we report observations of the DCO$^+/\text{HCO}^+$ ratio toward the dense gas of a cloud interacting with SNR W51C.

2. W51C, AN SNR INTERACTING WITH A MOLECULAR CLOUD

W51C (also known as J1923+141 and G49.2−0.7 in the literature) is a well known SNR at a distance of $\sim$6 kpc (Kundu & Velusamy 1967). The SNR extends about 30$'$ (equivalent to $\sim$60 pc), is about 3 $\times$ 10$^4$ years old (Koo et al. 1995), and is associated with a molecular cloud, engulfed by the blast wave, whose mass is $10^3 M_\odot$ and average density $\sim 10$ cm$^{-3}$ (Koo & Moon 1997). Five H II regions lie at the border of the SNR, the W51A, and B star-forming regions. Observations of H I and CO line emission have shown the presence of shocked material northwest, at about a distance of 10 pc from the center of the SNR (Koo et al. 1995; Koo & Moon 1997), where OH maser emission is also detected (Hewitt et al. 2008). In this work, we targeted five positions the molecular cloud (Table 1). Four of them lie a few arcminutes away from the shocked region, while one (point A) lies at the northern edge of it. An extended ($\sim$28 pc) GeV–TeV source has been detected by HESS (Feinstein et al. 2009) and Fermi Large Area Telescope (LAT; Abdo et al. 2009), with a total $\gamma$-ray luminosity of $\sim 10^{38}$ erg s$^{-1}$ cm$^{-2}$ (Abdo et al. 2009), making W51C one of the most luminous $\gamma$-ray sources of our Galaxy. Based on the observed GeV–TeV $\gamma$-ray spectrum, Abdo et al. (2009) claim that almost 99% of the observed $\gamma$-rays is due to the decay of $\pi^0$ mesons produced in inelastic collisions between accelerated protons and target gas.

### Table 1
Summary of Observations

| Species       | Transition | Frequency (GHz) | Main Beam Efficiency | HPBW (arcsec) | Telescope | Journal | Res. (MHz) | $T_{\text{sys}}$ (K) |
|---------------|------------|-----------------|----------------------|---------------|-----------|---------|------------|------------------|
| C$^{18}$O    | 1–0        | 109.782         | 0.79                 | 22            | IRAM      | 2009 May | 0.08       | $\sim 100$       |
| C$^{18}$O    | 2–1        | 219.560         | 0.79                 | 28            | APEX      | 2008 Dec | 0.5        | $\sim 230$       |
| $^{13}$CO    | 1–0        | 110.201         | 0.79                 | 22            | IRAM      | 2009 May | 0.08       | $\sim 100$       |
| $^{13}$CO    | 2–1        | 220.399         | 0.55                 | 12            | IRAM      | 2009 May | 0.08       | $\sim 100$       |
| $^{13}$CO    | 2–1        | 220.399         | 0.75                 | 28            | APEX      | 2008 Dec | 0.5        | $\sim 230$       |
| H$^{13}$CO$^+$| 1–0        | 86.754          | 0.79                 | 28            | IRAM      | 2009 May | 0.08       | $\sim 100$       |
| DCO$^+$      | 2–1        | 144.077         | 0.79                 | 17            | IRAM      | 2009 May | 0.08       | $\sim 100$       |

**Notes.** Parameters of the observations (upper half of the table). Observed positions with coordinates in J2000 and B1950 and line intensities main-beam temperatures (in K; lower half of the table). Numbers in parenthesis are statistical uncertainties at the 1σ level. Positions in the C column show two separate velocity components.

a APEX observations.

b IRAM observations: note that the second velocity component of the point C is not detected because the line is at the border of the filter.

3. OBSERVATIONS AND RESULTS

We observed five positions roughly sampling the cloud overlapping the HESS emission (Section 2; Table 1). To constrain the gas physical conditions, we observed the $^{13}$CO and $^{18}$O 1–0 and 2–1 transitions, while to measure the ionization degree, we observed the H$^{13}$CO$^+$ 1–0 and DCO$^+$ 2–1 transitions. The observations were obtained using the APEX and IRAM 30 m telescopes (Table 1). The amplitude calibration was done typically every 15 minutes, and pointing and focus were checked every 1 and 2 hr, respectively, ensuring $\sim$1–3$''$ accuracy. The APEX spectra were obtained in the classical ON–OFF mode, where the OFF at EQ 2000 coordinates 19:22:44.3, 14:05:50.0 shows no signal. The Fast Fourier Transform Spectrometer facility was used as a back end. For the IRAM observations, we used the VESPA autocorrelator and the frequency-switching mode. All spectra were reduced using the CLASS package (Hily-Blant et al. 2005) of the GILDAS software. Residual bandpass effects were subtracted using low-order ($\leq 3$) polynomials. Table 1 summarizes the observed signals at each point and each observed transition.

CO emission is detected in the four observed transitions in all points. H$^{13}$CO$^+$ 1–0 emission is, on the contrary, detected toward three positions only: A, C, and E. Finally, DCO$^+$ 1–0 emission is detected only toward the position E. The spectra toward the position E are shown in Figure 1. In general, there are two clouds in the line of sight, at different velocities $v_{\text{LRS}}$ around 69 and around 73 km s$^{-1}$, respectively. The line widths are similar in all points and transitions, about 3 km s$^{-1}$. The comparison of the $^{13}$CO 2–1 observed with APEX and IRAM gives a direct measurement of the emitting sizes. Points B, C, and E show extended ($\geq 28''$) emission, while in points A and D the sizes are about 20$''$. 

2
The Astrophysical Journal Letters, 740:L4 (5pp), 2011 October 10

Table 2
Analysis Results

| Position | $^{13}$CO/[C$^{18}$O] | Temperature (K) | Density ($10^5$ cm$^{-3}$) | N(C$^{18}$O) (10$^{15}$ cm$^{-2}$) | $A_v$ (mag) | Extent (arcsec) | N(H$^{13}$CO$^+$) (10$^{11}$ cm$^{-2}$) | [DCO$^+$/HCO$^+$] |
|----------|----------------------|-----------------|----------------------------|-----------------|-----------|----------------|-------------------------------|------------------|
| A        | 15                   | $>10$           | $>1$                       | 0.4–0.6         | 2–6       | 19             | 3–4                           | $<0.06$          |
| B        | 15                   | $>32$           | $>40$                      | 1.5–2.5         | 7–14      | 27             | $<0.002$                      |                  |
| C1       | 15                   | 23–28           | 6–20                       | 3.9–4.1         | 16–24     | $>28$          | 7–9                           | $<0.002$         |
| C2       | 10                   | $>27$           | 4–15                       | 1.3–2.5         | 8–14      | $>28$          | 6–8                           | $<0.006$         |
| D        | 10                   | $>10$           | $>1$                       | 0.2–0.9         | 1–5       | 20             | $<0.8$                        |                  |
| E        | 10                   | 21–24           | 8–20                       | 3.9–4.1         | 16–24     | $>28$          | 16–18                         | 0.0012–0.0016    |

Notes. $^{13}$CO/[C$^{18}$O] ratio, temperature, density, C$^{18}$O, and $A_v$ (assuming [C$^{18}$O]/[H$_2$] = 2 × 10$^{-7}$ (Frerking et al. 1982) and the usual N(H$_2$) = $A_v$ × 0.95 × 10$^{21}$ cm$^{-2}$ mag$^{-1}$), extent of the emitting region in arcsec, H$^{13}$CO$^+$ column density, and [DCO$^+$]/[H$^{13}$CO$^+$] abundance ratio (assuming [HCO$^+$]/[H$^{13}$CO$^+$] = 50) as derived by the analysis of the observed lines described in the text. The intervals account for the statistical uncertainty on the signals and on the physical parameters. To account for the uncertainty on the CO-to-$A_v$ ratio, the $A_v$ interval is increased by an additional 30%. Note that we run models with temperatures between 10 and 50 K and densities between 10$^3$ and 10$^5$ cm$^{-3}$ so that the lower limits apply to these intervals only.

4. ANALYSIS

4.1. Physical Conditions and Column Densities

We used the non-LTE LVG code described in Ceccarelli et al. (2003), with the CO–H$_2$ collisional coefficients by Wernli et al. (2006) for the first six CO levels and the temperature range 5–70 K. We run a grid of models with temperatures between 10 and 50 K, densities between 10$^3$ and 10$^5$ cm$^{-3}$, C$^{18}$O column densities between 1 × 10$^{14}$ and 4 × 10$^{16}$ cm$^{-2}$ and $^{13}$CO/C$^{18}$O ratio between 5 and 15. For each point, we used the extent derived by the comparison of the $^{13}$CO 2–1 line intensity obtained at APEX and IRAM telescopes, respectively. The values of the parameters minimizing the $\chi^2$ are reported in Table 2 (the range corresponds to $\chi^2 = 0.2$ contours). The H$^{13}$CO$^+$ column density has been derived by comparing the observed signals with non-LTE LVG computations using the collisional coefficients by Flower (1999) and the density and temperature derived from the previous step. The H$^{13}$CO$^+$ column density is then obtained by multiplying the N(H$^{13}$CO$^+$) by 50 (Koo & Moon 1997). Note that the [DCO$^+$]/[HCO$^+$] ratio very little depends on the actual gas temperature, for the range of temperatures considered here.

The clouds in the direction of points C1 and E have temperatures somewhat larger than 20 K, while the temperature is unconstrained in the other points. The densities are around 10$^5$ cm$^{-3}$ in points C1, C2, and E, and unconstrained in the other points. The visual extinction $A_v$ is a few magnitudes in points A and D, and it is larger than 10 mag in the other points. It is interesting and intriguing that points C1 and E have similar physical conditions but different column densities of HCO$^+$ and DCO$^+$.

4.2. Ionization Degree and CR Ionization Rate

Using the analytical method mentioned in Section 1 (Equations (1) and (2) in CWTH98), from the N(DCO$^+$)/N(H$^{13}$CO$^+$) ratio we derive an extremely high-ionization degree toward the point E, $x(e) \gtrsim 2 \times 10^{-5}$. This value is one or two orders of magnitude larger than those derived in other dark clouds by CWTH98. That point E is “special” with respect to the dark clouds of the CWTH sample that is indeed already clear from the observed signals: in those clouds the DCO$^+$ 1–0 line intensity is of the same order of magnitude than the H$^{13}$CO$^+$ 1–0 line intensity (Butner et al. 1995), whereas we observed more than 10 times lower DCO$^+$ 1–0 than the H$^{13}$CO$^+$ 1–0 line intensity. This is a hallmark that the ionization degree is much higher and does not leave much of uncertainty in this conclusion. However, the analytical method is an oversimplification, especially for high-ionization degrees, as more routes of HCO$^+$ formation become important in addition to the H$_3^+$CO one.

In order to correctly evaluate the chemical structure of the cloud toward the point E, including the penetration of the interstellar (IS) UV photons and a (more) complete chemical network, we used the photo-dissociation region (PDR) models.

---

Figure 1. Observations toward position E. From top to bottom: $^{13}$CO 2–1, $^{13}$CO 1–0, C$^{18}$O 2–1, C$^{18}$O 1–0, H$^{13}$CO$^+$ 1–0, and DCO$^+$ 2–1. The signals are in main beam temperature (in K). The vertical line shows 67 km s$^{-1}$.

5. We used the rate coefficients reported in database KIDA (http://kida.obs.u-bordeaux1.fr/).
by Le Petit et al. (2006). To help facilitate the discussion, Figure 2 shows the structure of a 20 mag cloud whose density is $1 \times 10^4$ cm$^{-3}$, like point E, illuminated on the two sides by the IS UV field and with different CR ionization rates. As found by several previous studies, for a low value of $\zeta$ ($\leq 10^{-16}$ s$^{-1}$) and a low abundance of metals, the ionization in the cloud is governed by the UV photons’ penetration and depends on the abundance of carbon ($A_c \leq 2$ mag) and sulfur ($2$ mag $\leq A_s \leq 4$ mag), and on the CR ionization deeper inside. The ionization at the interior of the cloud is low, $10^{-8}$ to $10^{-7}$, in a phase called low-ionization phase (LIP) in the literature (Pineau des Forêts et al. 1992). This situation is represented by the case $\zeta = 3 \times 10^{-17}$ s$^{-1}$ in Figure 2. In general, as $\zeta$ increases the ionization in the cloud interior ($A_c \geq 2$ mag) increases roughly quadratically until it reaches a critical point where it abruptly jumps to high values, in a phase called HIP (high-ionization phase). The LIP/HIP transition is a result of the nonlinear nature of the chemical network of molecular gas (e.g., Boger & Sternberg 2006; Rollig et al. 2007), which have been claimed to present a bistable nature (Le Bourlot et al. 1993). The spatial location of this transition depends upon various control parameters, among which the density, the abundance of He and metals, and the CR ionization rate (e.g., Wakelam et al. 2006). In practice, for a cloud of a given density, the LIP/HIP jump is governed by the metal abundances, specifically S, Si, Fe, and Mg going inward in the cloud, as metals are responsible for the (nonlinear) charge exchange. As shown by Figure 2, the zones closer to the cloud edge flip from LIP to HIP first, and the LIP/HIP jump moves further into the cloud with increasing $\zeta$, until the whole cloud is in HIP, regardless of the metal abundances.

The HCO$^+$ abundance is affected by $\zeta$ (the larger the $\zeta$ the larger the HCO$^+$ formation rate) and by the presence of the HIP region (the larger the ionization degree the larger the HCO$^+$ destruction rate). In general, the HCO$^+$ abundance is roughly divided into three zones: in the skin of the cloud, it is very low because of the photo-dissociation by the UV photons, deeper in the cloud it increases but the high ionization in the HIP region keeps the HCO$^+$ abundance low, and at still larger $A_c$ it increases, when eventually the gas jumps into the LIP.

The ratio $N$(CO)/$N$(HCO$^+$) of column densities, integrated over the 20 mag model cloud, is shown in Figure 3. It decreases with $\zeta$ (as the HCO$^+$ abundance increases), until a critical point (at $\zeta \sim (1.0-1.3) \times 10^{-15}$ s$^{-1}$ depending on the metals’ abundance) where the entire cloud is in the HIP state and the HCO$^+$ abundance becomes very low all across the entire cloud. Note that for high metal abundances the cloud is always in the HIP state. As noted by Wakelam et al. (2006), the ionization distribution is bimodal with the metal abundances. In fact, the theoretical $N$(CO)/$N$(HCO$^+$) ratio either follows the high or the intermediate metal abundance curves of our Figure 3.

The DCO$^+$ abundance follows qualitatively the behavior of HCO$^+$ and the HCO$^+$/DCO$^+$ ratio across the cloud depends on the ionization degree ($\sim 100$ in the LIP and $\geq 1000$ in the HIP zones, respectively). The dependence of the $N$(HCO$^+$)/$N$(DCO$^+$) ratio as a function of $\zeta$ is shown in Figure 3. In practice, the values of $N$(CO)/$N$(HCO$^+$) and $N$(HCO$^+$)/$N$(DCO$^+$) depend on the relative weight of the LIP-to-HIP zones in the integral over the cloud.

The comparison between the predicted $N$(CO)/$N$(HCO$^+$) and $N$(HCO$^+$)/$N$(DCO$^+$) ratios with the values observed toward the point E provides a value of $\zeta \sim (1.0-1.3) \times 10^{-15}$ s$^{-1}$. The likely structure of the cloud in the point E is shown in Figure 2. In practice, a large fraction of the cloud is the HIP state whereas the rest is in the LIP state. We stress, however, that, given the high nonlinearity of the equations, the exact value of $\zeta$ which fits the observations depends on the details of the adopted model (Wakelam et al. 2006; Boger & Sternberg 2006). Regardless of these details, the modeling indicates a situation where high (HIP) and low (LIP) ionization must be both present, to give the observed HCO$^+$/DCO$^+$ value which is an intermediate value of the two regions. The relative amounts of HIP/LIP may change with other control parameter values, but the result is that the line of sight we probe must contain both LIP and HIP. Finally, CRs...
heat the cloud as they deposit energy so that the relatively large value of the gas temperature (21–24 K) toward point E (Table 2) also favors the high $\zeta$.

Finally, the lower limit to $N$(HCO$^+)$/N(DCO$^+$) toward point C1 suggests a value for $\zeta$ larger than that in point E.

5. CONCLUSIONS

Our observations lead to two important conclusions.

1. The cloud toward point E has a CR ionization rate $\zeta \sim 10^{-15}$ s$^{-1}$, i.e., enhanced by about a factor of 100 with respect to the standard value (Glassgold & Langer 1974). This is the first time that such a high-ionization degree is measured in a dense molecular cloud. The fact that this cloud coincides with a TeV $\gamma$-ray source close to an SNR supports the idea that it is irradiated by an enhanced flux of freshly formed low-energy CRs. We have identified a location close to a CR accelerator with both enhanced low-energy CR ionization and high CR $\gamma$-ray emission, suggesting novel ways to study the acceleration and the diffusion of CR close to SN shocks.

2. The high low-energy CR flux induces the simultaneous presence of a region of high and low ionization, called HIP and LIP in the literature. To the best of our knowledge, this is the first time that such a situation has been observed and offers the possibility to study in more detail the chemistry of the two states simultaneously. Therefore, a more general implication of this work is that TeV sources identified with SNRs interacting with molecular clouds are promising sites not only for studying CR acceleration, but also for studying unusual chemical conditions.

REFERENCES

Abdo, A. A., Ackermann, M., Ajello, M., et al. 2009, ApJ, 706, L1
Aharonian, F. A., Akhperjanian, A. G., Bazer-Bachi, A. R., et al. 2008, A&A, 481, 401