Exploring the central molecular zone of the Galaxy using spectroscopy of \( \text{H}_3^+ \) and CO

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The central 400 parsecs of the Milky Way, a region known as the central molecular zone (CMZ), contains interstellar gas in a wide range of physical environments, from ultra-hot, rarified and highly ionized to warm, dense and molecular. The combination of infrared spectroscopy of \( \text{H}_3^+ \) and CO is a powerful way to determine the basic properties of molecular interstellar gas, because the abundance ratio of \( \text{H}_3^+ \) to CO in 'dense' clouds is quite different from that in 'diffuse' clouds. Moreover, the energy-level structure and the radiative properties of \( \text{H}_3^+ \) combined with the unusually warm temperatures of molecular gas in the CMZ make \( \text{H}_3^+ \) a unique probe of the physical conditions there. This paper describes how, using infrared absorption spectroscopy of \( \text{H}_3^+ \) and CO, it has been discovered that a large fraction of the volume of the CMZ is filled with warm, diffuse and partially molecular gas moving at speeds of up to approximately 200 km s\(^{-1}\) and that the mean cosmic ray ionization rate in the CMZ exceeds by roughly an order of magnitude values found in diffuse molecular clouds elsewhere in the Galaxy.

Keywords: interstellar medium; galactic centre; interstellar medium: molecules

1. Introduction

The centre of the Milky Way Galaxy is some 8 kiloparsecs (25,000 light years) distant from the Sun. The Galaxy’s central few hundred parsecs contain a 4 million solar mass black hole, Sgr A*, the densest concentration of stars in the Galaxy, three clusters of young and hot stars that somehow formed close to the centre several million years ago, and interstellar gas in environments ranging from extremely dilute and ultra-hot to dense (by astronomical standards) and warm. The other large galaxies in the Local Group are about 100 times more distant and other galaxy groups are much farther away than that. Thus, our Galaxy’s nuclear region can be observed in much greater detail than that of any other large galaxy.

Located between the Sun and the galactic centre (GC) are two outwardly moving arms of gas and associated dust as well as much gas and dust in circular motion about the nucleus. They cause two major complications. First, the dust absorbs and scatters essentially all of the visible light and a considerable fraction of the near-infrared light passing through it. Second, absorption lines arising in their gas contaminate the spectra of the gas located in the GC. These must be identified if one is to isolate the contributions of the GC’s gas.

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At the time of the discovery of \( \text{H}_3^+ \) in the GC astronomers thought that the gas within 200 pc of the very centre primarily existed in three distinct temperature and density regimes [1]. (i) Observations of molecular lines revealed the presence of about a half-dozen giant molecular (i.e. dense) clouds of temperatures of approximately 100 K, densities of approximately \( 10^4 \text{ cm}^{-3} \) and masses of approximately \( 10^6 \text{ M}_{\odot} \). They constitute the greatest concentration of molecular gas in the Galaxy [2]; because of that the region is called the central molecular zone (CMZ). While they may dominate the gaseous mass in the centre, they do not take up the majority of the volume. (ii) X-ray observations by low angular resolution space-borne telescopes showed extensive emission from very dilute and very hot plasma. Based on more recent observations, some of this emission is now known to originate in point sources [3], but the fraction of the volume filled by plasma may still be considerable. (iii) The angular sizes of radio point sources in the GC scale as \( \lambda^2 \), implying that their radio signals are scattered by density fluctuations in low-density (approx. \( 10 \text{ cm}^{-3} \)) ionized gas, probably located within the CMZ and possibly at the surfaces of its molecular clouds [1].

Since the discovery of very large amounts of \( \text{H}_3^+ \) in the GC 15 years ago, my colleagues and I have been combining high-resolution infrared spectroscopy of \( \text{H}_3^+ \) and CO in order to characterize the physical conditions of the gas in which the \( \text{H}_3^+ \) is located. Doing so has revealed the existence of a gaseous environment in the CMZ that is distinct from the three mentioned above and possibly is more extensive than any of them.

2. \( \text{H}_3^+ \) and CO as probes of molecular clouds: comparisons and contrasts

Interstellar molecular gas is largely found in two types of environments. In typical dense clouds, with \( n \sim 10^3-10^5 \text{ cm}^{-3} \) and linear dimensions of fractions of a parsec to a few parsecs, ambient galactic UV radiation does not penetrate beyond the surface layer of the cloud, the chemically active elements are essentially fully in molecular form, all carbon is in CO and the gas is neutral, apart from a small fraction ionized by cosmic rays. In diffuse clouds (\( n \sim 10-10^3 \text{ cm}^{-3} \) and sizes of one to many parsecs) only UV radiation capable of ionizing atomic hydrogen is blocked by the surface layers, and longer wavelength UV photons, capable of dissociating CO, ionizing atomic carbon and even photo-dissociating molecular hydrogen, penetrate deeply into the cloud. Typically, only about 1 per cent of the carbon is neutral and mostly in CO and only half of the hydrogen is in \( \text{H}_2 \).

The number densities of \( \text{H}_3^+ \) in these two types of clouds reflect balances between the \( \text{H}_3^+ \) production and destruction rates. In both types of cloud \( \text{H}_3^+ \) is produced by the cosmic ray ionization of \( \text{H}_2 \) to \( \text{H}_2^+ \) followed by the ion molecule reaction \( \text{H}_2^+ + \text{H}_2 \rightarrow \text{H}_3^+ + \text{H} \). It has recently been discovered that the ionization rate of \( \text{H}_2^+ \) in diffuse clouds is about an order of magnitude higher than its canonical value in dense clouds, \( 3 \times 10^{-17} \text{ s}^{-1} \) [4–6], with the difference being ascribed to a large population of low-energy cosmic rays that penetrate diffuse clouds but not dense clouds [4,7]. On the other hand, the rate coefficient for dissociative combination of \( \text{H}_3^+ \) on electrons [4], the dominant destruction mechanism in diffuse clouds, is about two orders of magnitude greater than the

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coefficient for the dominant destruction mechanism in dense clouds, the reaction \( \text{H}_3^+ + \text{CO} \rightarrow \text{HCO}^+ + \text{H}_2 \). In the steady state \( n(\text{H}_3^+) \) is about \( 1 \times 10^{-4} \) cm\(^{-3} \) in dense clouds and about one to two orders of magnitude less in diffuse clouds, depending on the fraction of hydrogen in molecular form there.

Because the linear dimensions of diffuse clouds are typically an order of magnitude greater than dense clouds the \( \text{H}_3^+ \) line strengths should be comparable in the two types of clouds, as is generally observed. However, CO is 100 times less abundant in diffuse clouds than in dense clouds, and the longer path lengths through diffuse clouds do not compensate for that difference. Thus, comparing the strengths of \( \text{H}_3^+ \) and CO lines can be a way to distinguish between diffuse and dense clouds.

### 3. Useful and unique properties of \( \text{H}_3^+ \)

One unusual property of \( \text{H}_3^+ \), alluded to in the previous section, is that, for steady-state conditions in clouds subjected throughout to a constant cosmic ray flux, \( n(\text{H}_3^+) \) does not scale with total density of the gas such as most other molecular species (e.g. CO), but instead is constant. Then the absorption path lengths through clouds scale directly with the column density of \( \text{H}_3^+ \). The column densities of most species are the integrals of their (varying and not well-known) number densities along the absorbing column.

Other valuable features of \( \text{H}_3^+ \) are related to its rotational energy-level structure (shown in figure 1) and the radiative transitions (or lack thereof) connecting them. For studies of the GC the most important of these is the metastability of the \((J, K) = (3, 3)\) state, 361 K above the lowest level. The strengths of absorption lines originating from that level compared with those from the \( J = 1 \) levels then

![Diagram of the three lowest rotational levels of \( \text{H}_3^+ \). Diagonal downward arrows denote allowed radiative transitions. The key levels \((J, K) = (1, 0), (1, 1), (2, 2)\) and \((3, 3)\) are labelled. (Online version in colour.)](image-url)
serve as thermometers if the gas is warm. The \((2, 2)\) level, intermediate in energy between the \(J = 1\) levels and \((3, 3)\), radiatively decays with a lifetime of 27 days and serves as a densitometer when \(n \sim 10^2 \text{ cm}^{-3}\). While diffuse clouds of that density are common, the temperatures of diffuse clouds outside of the GC are sufficiently low that the \(J = 2\) and 3 levels are not populated. As described below, the situation for the molecular gas in the GC is quite different.

4. \(\text{H}_3^+\) in the galactic centre: basic results from 1997 to 2008

The 1997 discovery spectra of \(\text{H}_3^+\) from \(J = 1\) levels towards the GC [8] were on sight-lines towards two objects, one located in the Central cluster near Sgr A* and one in the Quintuplet cluster, displaced from it by 30 pc in the plane of the sky. Both the absorption strengths and the velocity profiles (figure 2) demonstrate that the environment in which much of the \(\text{H}_3^+\) is located is significantly different from those previously observed. The velocity-integrated line strengths are as much as two orders of magnitude greater than previously observed in dense and diffuse clouds, despite total gas column densities being comparable to those in typical dense clouds and only factors of 3–10 greater than in diffuse clouds. The lines are also much wider, extending over 200 km s\(^{-1}\).

A major breakthrough came when spectroscopy of these two objects with much wider wavelength coverage revealed an \(\text{H}_3^+\) absorption line from the previously mentioned metastable \((3, 3)\) level [9], yet no absorption from the intermediate \((2, 2)\) level. The full implications of these findings did not become clear until higher resolution observations of \(\text{H}_3^+\) and of CO overtone lines were obtained [10]. These revealed that the profiles of the lines from \(J = 1\) levels consist largely of three narrow absorption features, corresponding to gas in circular orbits and the two arms mentioned earlier, situated on a 200 km s\(^{-1}\)-wide and nearly flat-bottomed ‘trough’ of blue-shifted absorption (figure 3). The spectra of low-lying CO lines

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Figure 2. Spectra of the \(\text{H}_3^+\ J = 1\) ortho–para doublet (rest wavelengths indicated by vertical lines) towards two objects in the GC obscured by \(A_V \sim 30\) mag [7], and towards the \(A_V \sim 3\) mag diffuse cloud towards \(\zeta\) Persei [3]. (Online version in colour.)
Figure 3. Spectra of the three lines of $\rm{H_3^+}$ and one line of CO towards the Quintuplet source GCS3-2 [9]. The dashed trapezoid at the top is the absorption ‘trough’ discussed in the text, present in the $\rm{H_3^+}$ $R(1,1)^l$ and $R(3,3)^l$ line profiles, but absent in the CO line profile.

also showed the narrow absorptions, implying that they are mostly associated with dense clouds in those arms. However, the CO lines lack the absorption trough present in the $\rm{H_3^+}$ line profiles. As discussed in §2, abundant $\rm{H_3^+}$ and a paucity of CO are characteristic of interstellar diffuse clouds. The large column density of the $\rm{H_3^+}$ that produces the absorption trough indicates that the diffuse gas is extensive within the CMZ.

The spectra of the $R(3,3)^l$ and $R(2,2)^l$ lines in figure 3 provide strong evidence for the above-mentioned conclusions. The $R(3,3)^l$ line shape is nearly identical to the trough in the $R(1,1)^l$ line; together those lines yield a temperature of approximately 250 K at all absorption velocities. Gas that warm and with such a wide range of velocities must be located in the GC. Finally, the lack of absorption by the $R(2,2)^l$ line indicates that the density of the trough gas is 100 cm$^{-3}$ or less, too low to significantly populate the $(2, 2)$ level by collisions.

Thus, the bulk of the GC $\rm{H_3^+}$ is located in a previously unidentified warm and diffuse environment. Its large column densities, observed on sight-lines between the Central and Quintuplet clusters, imply that $\zeta L$, the product of the cosmic ray ionization rate and the absorption path length through the diffuse gas in the CMZ, is nearly two orders of magnitude greater than in typical galactic diffuse clouds [9,11]. Considerable uncertainty exists concerning the mean value of $n(\rm{H_3^+})$ in the CMZ. Both $\zeta$ and the fraction of hydrogen in the form of $\rm{H_2}$ (which affects the $\rm{H_3^+}$ production rate) are unknowns. In addition, the electron density, which governs the destruction of $\rm{H_3^+}$, depends on the carbon abundance, which is not

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known although is generally thought to be considerably larger than the value in
the solar neighbourhood, based, for example, on the ratio of CO line intensity
to inferred H$_2$ column density in the central region of the Galaxy [12]. Even if
one assumes that the $\zeta$ is an order of magnitude higher than in galactic diffuse
clouds, values of $L$ are surely significant fractions of the radius of the CMZ [9,10].
Concluding that both the ionization rate is much higher than elsewhere and that
warm diffuse gas fills a large fraction of the CMZ, at least on these sight-lines,
seems inescapable.

5. Finding new sight-lines

Recent research using H$_3^+$ to study the CMZ has proceeded in two general
directions. One is the investigation of conditions very close to the centre, which
appear to be more extreme than elsewhere [11]. The other, described in this and
the following sections, is the determination of the extent of the warm diffuse gas.
As of 2008 observations of H$_3^+$ only sampled sight-lines from the Central cluster
to the Quintuplet cluster. The brightest stars in these two clusters and several
bright stars in between them were then the only objects known to be suitable for
spectroscopy of the rather weak lines of H$_3^+$.

To be suitable for such spectroscopy background point-like sources must: (i)
be sufficiently bright to be able to provide high-resolution infrared spectra at
high signal-to-noise ratios and (ii) have smooth intrinsic spectra that do not
contaminate the interstellar H$_3^+$ line profiles. Possibilities for such sources are
stars that are hot and luminous and stars with opaque circumstellar dust shells,
which convert the stellar spectra within to featureless and much cooler blackbody
spectra. However, no hot stars or stars with opaque dust shells of sufficient
brightness were known in the direction of the CMZ apart from those close to
or within the Central and Quintuplet clusters.

The CMZ is filled with bright infrared sources, but very little is known about
them individually. Everywhere except in the three clusters of hot stars, the
overwhelming majority is expected to be red giants, whose complex photospheric
spectra make them unsuitable as probes of H$_3^+$ in the interstellar medium. To
find bright objects in the CMZ with smooth spectra, one must first identify likely
candidates, next determine by observations if they are either hot stars or stars
embedded in dusty shells, and then undertake the much more time-consuming
high-resolution spectroscopy of H$_3^+$ and CO to establish the approximate locations
of the objects (in front of, within, or behind the CMZ) and determine the physical
state of the absorbing gas, as in figure 3.

Since 2009, we have been using the Two Micron All Sky Survey (2MASS)
point source catalogue [13], which provides photometry in the $J$, $H$ and $K$
bands (covering 1.0–2.5 $\mu$m), and the Spitzer Space Telescope GLIMPSE II catalogue
[14,15], containing photometry in four passbands between 3.5 and 8 $\mu$m, to
identify bright objects in the direction of the CMZ that are likely to have opaque
dust shells. The technique is far from foolproof, both because some red giant
photospheres are very cool and because the effects of high extinction and low
temperature on 1–8 $\mu$m photometric fluxes cannot be easily separated. We use
low-resolution spectroscopy in the $K$ band to discriminate between red giants and
dust shells, as the former have absorption bands of hot CO in the long wavelength
part of that band. To date, we have identified approximately 300 candidates out of the total of 2,000,000 objects in the GLIMPSE catalogue in our search area. Two-thirds of those candidates have been observed; of them approximately 30 have smooth-infrared spectra suitable for high-resolution spectroscopy.

Figure 4 shows results of the search as of the end of 2011. It can be seen that there is now a sample of suitable objects whose sight-lines cover a much wider extent of the CMZ than as of 2008. High-resolution spectra of key lines of H$_3^+$ and CO have been secured for some of these. Below, we discuss two of the more interesting cases.

6. New spectra on new sight-lines

Figure 5[16] shows spectra of H$_3^+$ and CO lines towards two new sources, labelled α and i in figure 4, whose 2MASS catalogue names are J17433273–2951430 and J17470898–2829561 (hereafter J1743 and J1747), respectively. The H$_3^+$ $R(1,1)^l$ line profile towards J1743 consists of four narrow absorption features, three of which correspond to dense clouds known from previous radio and millimetre observations. The fourth, at a radial velocity of zero, arises in warm diffuse gas, as demonstrated by the lack of CO absorption at that radial velocity and by the presence of $R(3,3)^l$ absorption at that radial velocity [17]. Zero velocity would be expected for gas with pure outward motion lying in front of J1743, because that source is located on a sight-line passing close to the western edge of the CMZ, where radial motions of CMZ gas are perpendicular to the line of sight.

The spectra of J1747 in figure 5 are complex, because it is embedded within the giant molecular cloud Sgr B, a hotbed of turbulence and massive star formation. The array of absorption features at positive velocities is associated with this cloud, and the sharp features near −30 and −50 km s$^{-1}$ with the intervening arms.
Figure 5. Velocity profiles of H$_3^+$ and CO lines towards (a) J1743 and (b) J1747 [15]. Downward arrows denote absorptions of H$_3^+$ in warm and diffuse CMZ gas. Absorption components likely to be associated with Sgr E, Sgr B and spiral arms are indicated. (Online version in colour.)

absorption in the H$_3^+$ R$(1, 1)^j$ line near $-100$ km s$^{-1}$ has little or no counterpart in CO, indicating that the gas cloud producing it is diffuse. Absorption in the R$(3, 3)^j$ line [17] at that velocity indicates that gas also is warm and therefore is in the CMZ. The velocity is roughly as expected in view of Sgr B’s offset from the centre of roughly half the radius of the CMZ.

7. Conclusion

The data in hand suggest strongly that warm and diffuse gas is pervasive in the CMZ and is not limited to the sight-lines close to the Central and Quintuplet clusters where it was first discovered. A CMZ-filling factor of approximately 10 per cent seems to be required at minimum. It is surprising that $nT$ for this gas, approximately $2 \times 10^4$ cm$^{-3}$K, is at least an order of magnitude less than those of the other gas phases, and suggests that the overall configuration of gas in the CMZ is highly dynamic. The cause of the outwards movement of the warm and diffuse gas is unknown. Is the gas responding to an ejection event, the gravitational potential of a galactic bar, or some other stimulus? Important for addressing this question will be spectroscopy of objects located behind the GC and perhaps completely behind the CMZ. Finding suitable objects may prove difficult because of the greater extinction, but they will inevitably be found and used as larger telescopes and higher sensitivity infrared spectrographs are built and take their place among the observers’ tools.

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Appendix A. Recollections of 10–11 July 1997

The events that took place on the night of 10–11 July 1997 at the United Kingdom Infrared Telescope (UKIRT) on Mauna Kea are crucial to our current understanding of H$_3^+$ in the interstellar medium, including the GC. That night was Oka’s and my first night of observing together since confirming the detection of H$_3^+$ in two dense molecular clouds towards the infrared sources W33A and GL 2136 1 year earlier. We had requested and been granted time at UKIRT to conduct a survey of H$_3^+$ in molecular clouds, using the close pair of absorption lines near 3.67 μm. Ben McCall, Oka’s new graduate student, joined us. Oka and I expected that the data that we would obtain from the survey would form the main observational part of Ben’s thesis. However, the time granted to us, two nights, was insufficient to observe all of the clouds on our list.

In addition to sight-lines through standard dense clouds, our target list included one object in the GC, IRS 3, one of the brightest sources at 3.67 μm in the Central cluster. The interstellar gas on the line of sight to the GC, however, is not located entirely in dense clouds. Although that sight-line passes through such clouds in the intervening galactic arms, it also traverses other gaseous environments. The sight-line is a hodgepodge. I recall thinking that if we succeeded in detecting H$_3^+$ towards IRS 3 we would not understand what it meant, and if we did not succeed we also would not understand it. I was thus tempted to skip IRS 3 and concentrate on observing objects embedded in pure dense clouds, whose properties were at least somewhat understood and which would be likely to teach us something useful. Adding to this feeling was that IRS 3 is considerably fainter than our other targets; if the H$_3^+$ lines towards it were about the same strength as those detected towards W33A and GL 2136, they would require a long time to detect and we would not make as large a dent in the survey as we hoped.

However, as Sagittarius rose in the sky that evening, I concluded and Oka agreed that we should observe IRS 3. It was, after all, in the galactic centre, a unique and fascinating place. And so we did, with stunning results. The integrated absorption by the doublet was nearly two orders of magnitude greater than towards either W33A or GL 2136 and its velocity extent was over 200 km s$^{-1}$. The total absorption strength in particular was incomprehensible to us, as the extinctions towards W33A and GL 2136 each equalled or exceeded that towards the GC. To see if we were somehow fooling ourselves, we observed another ground state line towards IRS 3 and found that it was about as strong as the lines making up the doublet. We then pointed the telescope at a much brighter object, GCS3-2, located in the GC region but roughly 30 pc east of IRS 3. The strong H$_3^+$ absorption was immediately apparent.

We resumed the molecular cloud survey while searching for an explanation. I knew that a strong 3.4 μm absorption feature was also present towards the GC and indicated that a significant fraction of the gas in front of the GC was in diffuse clouds. Could some of the H$_3^+$ absorption be arising in that environment? Our understanding at that time was that a uniform cosmic ray ionization rate was
present in all galactic interstellar clouds. We also thought that in diffuse clouds the H$_3^+$ was likely to be quickly destroyed by dissociative recombination on electrons (the value of the rate coefficient for that reaction was then highly uncertain, but we suspected that, as was found later, it was at the high end of the range of measured and theoretical values). Thus, it seemed impossible that H$_3^+$ could be present in detectable quantities in diffuse clouds, let alone in the huge amounts we had just detected. Nevertheless, perhaps we should observationally rule out large amounts of H$_3^+$ in diffuse clouds by looking for it in a well-understood example. I was not well versed in the study of the diffuse interstellar medium, but I did know of one prototypical diffuse cloud sight-line—that towards the star Cygnus OB2 no. 12. Fortunately, that star would be observable at UKIRT later that night.

Fifteen years ago, it was acceptable, albeit unusual, to add new targets to an approved UKIRT programme in real time, as long as the new observations did not conflict with other science being undertaken at the telescope, and I knew our observing programme was unique. Therefore, in the middle of the night, we pointed the telescope to Cygnus OB2 no. 12. To our amazement, an easily detectable H$_3^+$ doublet popped up in the first few minutes, comparable in strength to those we had found towards W33A and GL 2136. Once again we were stunned and, being fans of H$_3^+$, we were also ecstatic. The column density of H$_3^+$ seen towards Cygnus OB2 no. 12 was more than an order of magnitude more H$_3^+$ than we had expected. And yet even that, scaled up to account for the difference in interstellar extinctions, could not explain the huge amount of H$_3^+$ detected towards the GC.

Thus, the night of 10–11 July yielded two remarkable discoveries [8,18], and we ended that night with two wonderful puzzles on our hands: how could there be so much H$_3^+$ in diffuse clouds; and, even if H$_3^+$ were much more abundant in diffuse clouds than we had thought, how could there be such a vast amount of H$_3^+$ on GC sight-lines. Answering those questions has kept us and others busy for the last 15 years and will probably continue to do so for many years to come.

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