TWENTY-FIVE YEARS OF CO ASTRONOMY: REVEALING THE COLD UNIVERSE

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1. Introduction

I suspect that future historians of science will regard the discovery of CO in space as one of the more significant milestones of astronomical research in the 20th century — a period which is likely to be considered the Golden Age of astronomical discovery. It was during this century that such fundamental phenomena as galaxies, the big bang, the expanding universe, the interstellar medium, quasars, pulsars, black holes, extra-solar planets and protostars were first revealed by observational exploration. Indeed, it was also in this century that observation and theory combined to decipher the very nature of the stars themselves as thermonuclear reactors which convert hydrogen, the primary product of the big bang, into the zoo of heavier elements which make up the periodic table. These discoveries were the direct result of the dramatic evolution of observing technology which among other things, opened the entire electromagnetic spectrum to astronomical investigation and enabled observations at optical, radio, infrared, UV, X and γ ray wavelengths with large telescopes on the ground, in the air and in space.

The discovery of interstellar CO emission in 1970 was a consequence of the quest to open the millimeter-wave portion of the electromagnetic spectrum to astronomical research and it ushered in a whole new era in the study of the interstellar medium and star formation. Its significance to astronomy lies in the fact that observations of CO (more than any other tracer) revealed to astronomers a new component of the cosmos: *the cold universe*. This is the universe of birth and creation. It is the universe where planets, stars and perhaps even galaxies come into being. It is the universe where the interesting physical mechanisms are not those which produce ever increasing amounts of energy, but those which produce ever decreasing amounts of entropy. It is the astrochemical universe of molecules and dust. Before the discovery of CO the cold universe was an unknown and uncharted frontier of astrophysics. With the discovery of CO, the cold universe became the subject of detailed astronomical scrutiny and CO observations have proved to be the primary probe for its exploration.

2. State of Affairs Prior to 1970

By the middle of the twentieth century, such observations as: 1) the discovery of stationary atomic absorption lines in the spectra of spectroscopic binary stars (Hartmann 1907; Plaskett and Pearce 1933), 2) deep photographs of dark nebulae within the Milky Way (e.g., Barnard 1919) and 3) the general extinction of starlight toward open clusters (Trumpler 1930), had convinced most astronomers of the existence of an interstellar medium (ISM) of gas and dust. The discovery of HI emission at λ21 cm in 1951 revealed in dramatic fashion just how pervasive the interstellar gas was in the disk of the Milky Way. By the 1960s radio and optical observations of atomic clouds and HII regions, as well as of dust polarization and extinction contributed to an extensive body of literature (both theoretical and observational) dealing with the subject of interstellar gas and dust in the galaxy (e.g., Dufay 1957). Although the basic physical processes (e.g., cooling, heating, ionization, interaction with stellar radiation fields, etc.) seemed well understood (e.g., Spitzer 1968), the basic structure of the interstellar medium was not at all clear. In particular, it was not certain whether or not the interstellar medium was in fact a medium. That is, whether it was made up of smoothly distributed gas and dust, or of a collection of discrete clouds. By 1970, however, an elegant theoretical picture of the ISM was developed. Simple considerations of the equilibrium heating and cooling balance in atomic clouds suggested that the interstellar gas likely existed in only one of two stable phases: a high density cool phase which could be identified with discrete clouds and a low density warm phase which could be identified with an "intercloud" medium (Field, Goldsmith and Habing 1969). On another front the development of the theory of stellar structure and evolution by the middle of the century led to an understanding of the basic nature of stars and their evolution on and off the main sequence. Although this theory is one of the greatest achievements of 20th century astronomy, by 1970 (and even at present) it was incomplete in one very fundamental aspect: it did not predict or explain the origin of stars. As a result the problem of star formation became a prime focus of ISM research in the latter part of the century. In the two-phase ISM picture, star formation presumably occurred in the cool atomic clouds through some process of global collapse and hierachical fragmentation (e.g., Hoyle 1953; Spitzer 1968).

Unfortunately, this tidy picture of the ISM and star formation quickly came into conflict with numerous observations. For example, HI clouds were observed over a wider range of temperatures than appeared permitted by the theory. In addition, optical and X-ray observations uncovered a major and very hot ($\approx 10^6$ K) component of insterstellar gas not predicted by the two phase theory. Moreover, the youngest known low mass stars were found intimately associated with dark nebulae (e.g., Herbig 1962) which were not, as it turns out, the HI clouds envisioned by the theory of the two phase ISM. Although HI column densities were generally proportional to dust column densities (e.g. Lilley 1955), HI was either weak or entirely absent in dark nebulae (e.g., Bok, Lawrence & Menton 1955; Heiles 1969), the regions of highest visual extinction, suggesting that the gas that made up these nebulae was molecular not atomic in nature. With the discoveries of radio transitions of OH, H_2O and NH_3 in space, the significance of a molecular phase of the ISM became increasingly apparent. By 1970 the stage was set for a major shift in paradigm.

3. CO and the Cold Interstellar Medium

When it was discovered in 1970, both the strength and the ubiquity of CO emission in space were a complete surprise (Wilson et al. 1970; Penzias et al. 1971). Indeed, the fundamental rotational transition of CO was detected in emssion toward HII regions, dark nebulae, Bok Globules, reflection nebulae, supernova remnants, planetary nebulae and even in the extended atmospheres of certain luminous infrared giant stars. Moreover, in regions where it was found, emission from CO was more widespread than any other molecular tracer known at that time or subsequently discovered. It was found essentially everywhere there was a significant amount of extinction (i.e., $A_v > 1$ magnitude). The excitation of this transition by collisions required sufficiently high densities (100-1000 cm^{-3}) that it was clear that CO clouds had to be composed primarily of hydrogen. Furthermore, the lack of observable HI emission in such regions indicated that the hydrogen had to be in molecular form. It became quickly apparent that emission from the $J = 1 \rightarrow 0$ transition of CO was very effectively tracing the (cold) molecular component of the interstellar medium. And this was the component of the ISM where star formation occurred. It was the cold, dense gas that proved to be so impenetrable to the optical observations of the first half of the century.

Surveys of CO emission in the disk of the Milky Way soon revealed the unexpected result that cold molecular gas constituted a significant fraction of the ISM: in the vicinity of the Sun, as much as half the mass of the interstellar medium was in the form of molecular clouds while a considerably higher fraction of the interstellar gas was molecular in form in the inner and central regions of the Galaxy (e.g., Combes 1991 and references therein). Besides this significant finding, CO mapping of molecular clouds led to two other discoveries of fundamental importance for astronomy: Giant Molecular Clouds (GMCs) and bipolar molecular outflows. These latter two discoveries helped to revolutionize the study of star formation and thus merit further brief discussion.

3.1. GIANT MOLECULAR CLOUDS (GMCS)

With sizes between 50–100 parsecs in extent, GMCs are the largest objects in the Galaxy and with masses between 10^5–10^6 $M_\odot$, they rival globular clusters as the most massive objects in the Milky Way. With temperatures seldom exceeding 10 K, GMCs are the coldest objects in the universe, yet their existence was unknown prior to 1970. Over the last twenty years, observations have established that GMCs are the sites of all star formation currently taking place in the Milky Way. In the 1970s CO mapping of GMCs revolutionized the way astronomers viewed the problem of star formation (e.g., Tucker, Kutner and Thaddeus 1973; Lada 1975; Loren 1975; Elmegreen and Lada 1977; Blitz 1980). During the preceding twenty years observations of giant HII regions, compact HII regions, H_2O and OH maser sources, infrared stars and Herbig-Haro objects provided a menagerie of astronomical phenomena that were thought to be somehow intimately related to the processes of star formation and early stellar evolution. Yet, the true natures of most of these objects as well as their precise relation to each other and to the actual process of stellar birth were obscure. GMCs provided a unifying context within which these phenomena could be linked together. The underlying physical connection was that all these interesting objects were inhabitants of GMCs. Moreover, within a given GMC the various objects were often simultaneously present. This gave rise to the notion that these seemingly disparate phenomena could be understood as manifestations of differing stages in the development of young stars within a star forming molecular cloud complex. And, this notion gained considerable support from subsequent observations and theoretical modelling of the infrared energy distributions of embedded young stellar objects (e.g., Adams, Lada and Shu 1987).

Yet after twenty-five years of research, many basic questions concerning the nature of GMCs remain unanswered. These include the questions of their origin, evolution, death, and physical structure. For example, we do not know if GMCs are formed from HI clouds, the intercloud medium, smaller molecular clouds, or all of the above. It is likely that cloud formation involves spiral density waves, supernova explosions, the galactic dynamo, photoionization by galactic starlight and maybe other phenomena (e.g., Elmegreen 1991), but, unfortunately, observations and theoretical understanding of many of these processes are still lacking and the origin of the largest and most massive objects in the Galaxy remains a complete mystery. Likewise, we are not sure how GMCs die. They are probably destroyed by OB associations. But are they converted into ionized and/or atomic gas or are they shredded into smaller molecular cloud chaff? What are the timescales for their formation, evolution and destruction? The critical observations needed to answer these questions either don't yet exist or are not fully recognized, a circumstance which indicates how deep our lack of understanding of these problems actually is. Much of this uncertainty surely results from the fact that there is not as yet a clear picture of molecular cloud structure. Molecular-line observations certainly indicate that GMCs are highly structured, but finding a meaningful way to characterize this structure has proved to be surprisingly elusive. Are clouds composed of (round) clumps, (elongated) filaments, or is their structure best described by chaotic complexity? Do we even know what we really mean by any of these terms? It is difficult to see how progress will be made in this area since existing molecular-line data are about as detailed as one could hope to obtain and furthermore are unlikely to be surpassed by any future observations. A fundamental revision of the manner in which we think about cloud structure may be required to make appreciable progress in understanding these issues.

3.2. BIPOLAR MOLECULAR OUTFLOWS

About a decade after the discovery of CO, CO observations of the molecular gas surrounding certain young stellar objects led to the discovery an unanticipated phenomenon of great significance for understanding the process of star formation. In mapping the velocity field around the infrared source known as L1551 IRS 5, Snell Loren and Plambeck (1980) discovered the first example of a bipolar outflow of cold molecular gas emanating from a buried protostellar object. This discovery came as a complete surprise because up until that time it was generally believed that if there were any systematic bulk motion of material in a molecular cloud, especially around a protostellar object, that motion should be collapse, not outflow (e.g., Goldreich and Kwan 1974). Subsequent CO observational surveys revealed many more bipolar outflow sources (e.g., Bally and Lada 1983) so that at the present time well over 100 molecular outflows are known, most within a kiloparsec of the sun (e.g, Fukui et al. 1993). Their properties have been extensively and thoroughly reviewed in the literature (e.g., Lada 1985, Bachiller & Gomez-Gonzalez 1992). Briefly, the masses of such outflows are substantial, containing anywhere between 0.1 and 100 solar masses. Consequently, the outflowing molecular gas consists of swept-up ambient cloud material rather than original ejecta from the driving source. More significantly, the corresponding kinetic energies of the flows are enormous, ranging between 10^{43} and 10^{47} ergs! The dynamical timescales of the flows are estimated to be between 10^3 and 10^5 years and their local formation rate is estimated to be roughly comparable to the formation rate for stars of a solar mass or greater. Taken together, these facts suggest that molecular outflows play a critical role in the star formation process. In particular, bipolar molecular outflows are individually energetic enough to disrupt cloud cores and it is suspected that they are the likely agent that drives the evolution of a young stellar object from the deeply embedded protostellar stage to the optically revealed pre-main sequence stage of early stellar evolution.

At the same time the coincidence of bipolar outflows with protostellar objects presented an interesting paradox for star formation researchers: How can a protostar—an embryonic stellar core in the process of accreting matter and building up a stellar mass—be simultaneously a source of outflow and inflow? How can a star form by losing mass? The answer to these questions lie at the heart of the star formation problem. Because of its conservation, angular momentum presents a barrier which prevents the contraction of interstellar gas to stellar dimensions. Although magnetic breaking during the early stages of cloud formation and the process of viscous accretion through a circumstellar disk can remove a significant amount of the initial angular momentum of an accreting element of interstellar gas, the gas still retains too much specific angular momentum to reach a configuration of stellar dimensions. If generated close enough to an embryonic star, bipolar outflows can, in principle, carry away significant amounts of angular momentum and thus enable the accretion process to build up a protostellar embryo to stellar mass. Evidently, bipolar outflows may be the physical process employed by nature to solve the angular momentum problem of star formation and in doing so thus resolve the paradox of the simultaneity of outflow and infall in protostellar evolution (e.g., Shu et al. 1988).

In many respects more may be understood about the fundamental aspects of bipolar outflows than is understood about the fundamental aspects of GMCs. For example, the origin of the bipolar outflow phase is thought to be a natural consequence of the formation of a star while the cessation of the outflow phase a result of the termination of the accretion process which occurs at that point when the build up of a young star comes to an end. However, there are still many basic aspects of the bipolar outflow phenomenon that are mysterious. For example, the physical mechanism that accelerates the primary wind driving the molecular outflow is not understood, neither is the mechanism that produces the bipolar, often jet-like morphology observed in CO maps. In addition, it is not clear how the primary wind actually sweeps up the large masses of cold ambient molecular gas that make up the bipolar lobes of an outflow. Nevertheless, the discovery of bipolar molecular outflows by CO observations has provided a most critical piece to the ultimate solution of the star formation puzzle.

4. CO and the Cold Component of Galaxies

In the limited space I have remaining I will briefly outline the tremendous impact of CO observations on the studies of the Milky Way and extragalactic astronomy. Not long after its discovery, CO observations were employed to investigate the structure of the Milky Way, and as receivers, spectrometers and telescopes improved, the structure and properties of the cold component of external galaxies. Early studies showed that the distribution of the molecular gas in the Milky Way differed significantly from that of atomic gas. Cold molecular gas was found to be primarily located in a ring between 4 and 8 kiloparsecs from the Galactic center with an additional strong concentration in the inner region of the Galaxy (e.g., Scoville and Solomon 1975, Burton et al. 1975). In these two regions of the Galaxy the ISM is primarily molecular, while outside the solar circle it is primarily atomic. Although not perfect, CO also turned out to be a much better tracer of spiral structure than HI, revealing strong spiral features in the outer as well as inner Galaxy (e.g., Cohen et al. 1980; Dame et al. 1986). CO observations also enabled the rotation curve of the Galaxy to be determined well beyond the solar circle and thus provided a more accurate weighing of the Milky Way than previously possible (e.g., Blitz 1979). The resulting increase of about a factor of 2 in its mass led to the recognition of "... A bigger and better Milky Way..." as Bart Bok once put it. More recently, examination of the kinematics of molecular gas in the inner Galaxy has helped lead to the recognition that our Galaxy is likely a barred spiral (Liszt and Burton 1980, Binney et al. 1991), and this is something that can perhaps account for the absence of molecular gas between 1–4 kpc, a feature which is not present in the molecular component of most normal spiral galaxies. CO observations also revealed the very unusual nature of the ISM in the inner regions of the Galaxy, where GMCs reach masses in excess of 10^6 $M_\odot$ and average densities two orders of magnitude higher than those characteristic of GMCs in molecular ring (e.g., Bally et al. 1988)!

The significance of CO studies for external galaxies lies in the fact that star formation drives galactic evolution. Star formation takes place in GMCs and CO is by far the best tracer of cold molecular gas that we have at our disposal. Over the last twenty years or so, CO observations have been successfully used to probe the cold component of hundreds of external galaxies (e.g., Young and Scoville 1991 and references therein). In nearby galaxies such as M31 and M33, interferometric and single dish observations have been able to resolve individual GMCs enabling estimates of their sizes, masses and densities. The molecular component of spiral arms has been very clearly traced out in at least one galaxy, M51. Such observations enable the investigation of such issues as GMC formation and destruction in a manner not possible for Milky Way clouds and may be the best way to investigate these problems. In more than 100 spiral galaxies the radial distribution molecular gas has been determined from CO mapping. Among the interesting results that have been found is the fact that the radial distributions of CO in most spiral galaxies have central peaks and then fall off monotonically with increasing radial distance from the center. This differs from the Milky Way which, as mentioned earlier, has a depression between 1-4 kpc and a ring-like appearance. On the other hand, these galaxies are similar to the Milky Way in that the distributions of HI and CO in them are distinctly different. The ratio of atomic-to-molecular hydrogen has also been measured in many galaxies and found to be dependent on galactic type. Although such determinations as well as the overall H_2 mass determinations for galaxies appear to still be plagued by the uncertainty in the conversion of CO luminosities to hydrogen masses.

Some of the most interesting results have come from studies of the nuclear regions of galaxies. CO observations have enabled measurements and in some cases mapping of the molecular contents of active nuclear regions of nearby galaxies such as M82 and NGC 1068 where similar to the nuclear region of our galaxy, gas densities are significantly higher than found in the GMCs of the disk. Particularly intriguing are the observations of ultraluminous infrared galaxies. Many of these systems appear to be interacting or merging galaxies and all appear to be rich in molecular gas which is highly concentrated in their nuclear regions. Moreover, evidence suggests that the mass of molecular material is comparable to the dynamical mass (Scoville et al. 1991) suggesting that whatever is being formed in these regions (e.g., the nuclear bulge of a merged galaxy) is in a very early stage of development. The detection of the lensed, ultraluminous galaxies F10214+4724 and the Cloverleaf seem to indicate that ultraluminous starbursts are important even at relatively large look back times (i.e., $z \approx 2$). Clearly, observations of the cold molecular component of external galaxies are telling us something about the evolution and perhaps even the formation of galaxies. What exactly that is remains to be determined by future research.

5. Concluding Remarks

The preceeding brief discussion of the impact on astronomy of 25 years of CO observations would take hundreds of additional references and many figures to properly document. Even so, it would be still far from comprehensive and would require many more pages of text to do justice to the wide range of exciting research which has resulted from the opening of the cold molecular universe to astronomical investigation a quarter century ago. The reader has only to skim the table of contents of this volume to appreciate both how much was left out of this short review and the true scope of present day research on this topic. However, I hope I have conveyed here some sense of the remarkable progress achieved as a result of the early exploration of the cold universe by CO observations. This conference marks not only the end of the first 25 years of CO astronomy but also the beginning of a new quarter century of vigorous exploration of a universe which has not yet revealed all its secrets. Young astronomers take heart, there is still much left to decipher.

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