How Interstellar Chemistry (and Astrochemistry More Generally) Became Useful

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In 1986 Alex Dalgarno published a paper entitled *Is Interstellar Chemistry Useful?* By the middle 1970s, and perhaps even earlier, Alex had hoped that astronomical molecules would prove to: possess significant diagnostic utility; control many of the environments in which they exist; stimulate a wide variety of physicists and chemists who are at least as fascinated by the mechanisms forming and removing the molecules as by astronomy. His own research efforts have contributed greatly to the realization of that hope. This paper contains a few examples of: how molecules are used to diagnose large-scale dynamics in astronomical sources including star forming regions and supernovae; the ways in which molecular processes control the evolution of astronomical objects such as dense cores destined to become stars and very evolved giant stars; theoretical and laboratory investigations that elucidate the processes producing and removing astronomical molecules and allow their detection.

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1. Introduction (by T. W. Hartquist)

Jane Fox's eloquent comments about Alex Dalgarno's qualities as a friend, made at the September 2008 symposium honoring him, provided a fitting tribute to Alex's generosity, kindness and thoughtfulness. I am privileged to have Alex as a friend and also to have benefitted from his professional and intellectual support.
Many of Alex’s former students and postdocs, as well as other colleagues, have stories about him similar to those that I will relate. We should all wonder how many letters of recommendation Alex has written. That activity must have consumed a tremendous amount of time. However, Alex’s professional support of others has often gone far beyond letter writing. He has visited many of us shortly after our moves to new positions and has helped us make good impressions on our new colleagues. In Leeds, as elsewhere, he served on a visiting panel providing advice on how the local physics and astronomy research effort might be developed. The other two panelists visited one day each. In contrast, over a three day period, he spoke one-on-one with every available permanent member of our Physics and Astronomy academic staff to gain a complete and thorough overview of our activity. He produced an insightful report, which due to its concise, reasoned and incisive nature, carried considerable impact. It contributed very positively to our subsequent, successful efforts to establish a new group, with four permanent academic posts, conducting theoretical research on fundamental quantum processes. Alex continued to help Leeds after his 2003 stay. In 2007 he served as an external member of the committee that appointed Paola Caselli as our Professor of Astronomy.

In 1975 when I, as a postgraduate student, first worked with Alex, I soon developed interests in hydromagnetics and plasma kinetics. Rather than encourage me to focus only on molecular processes, Alex supported my other interests. One problem that I wished to pursue concerns the screening of molecular clouds from ionizing cosmic rays by scattering on Alfvén waves. Alex kindly arranged for me to spend substantial fractions of the summers of 1976 and 1977 in Cambridge, England. While there in 1976, I received a letter from him drawing my attention to a recently published paper by Skilling and Strong on that topic. Alex has often astounded others with his encyclopedic knowledge of a tremendous range of literature. His awareness of so much has often been of great help to others. Alex, Holly Doyle and I made use of results in Ref. 2 in a paper on ionization rates inferred for diffuse molecular clouds.

The title of the present paper echoes that of a paper by Alex to which John Black and Ewine van Dishoeck also referred during their talks at the September 2008 symposium. The remainder of this paper is divided into six sections, half of which mention selected contributions of Alex primarily in molecular astrophysics. My coauthors and I have divided his contributions into those concerning molecular diagnosis, those showing how molecular processes control astrophysical environments and those in the investigation
of quantum processes relevant to astrophysics. Sections addressing selected recent works on these themes by other researchers interleave with those summarizing Alex’s efforts. I apologize to Alex and to others for the fact that the selections cannot be comprehensive. We have had to neglect a great deal of excellent work done by Alex and by others. Ewine gave a talk at the symposium in which she summarized some of Alex’s work in astrochemistry and some recent work of others. The overlaps and the differences between what she said and what I said demonstrate the strength and breadth of Alex’s work and of the current state of molecular astrophysics.

2. Alex’s Work on Diagnostics

The Copernicus satellite, launched in August 1972, enabled far ultraviolet spectroscopy of the nearest O and B stars and of diffuse interstellar matter along the lines of sight to them. Alex and his students and other collaborators developed the framework and tools to use Copernicus data to probe the natures of diffuse molecular clouds, those molecular clouds having optical depths at visual wavelengths less than about unity. Black and Dalgarno interpreted absorption measurements of the column densities of atomic hydrogen, the ground and next lowest six rotational levels of $\text{H}_2$, HD and OH for the line of sight to $\zeta$ Oph. They inferred the intensity of the far ultraviolet radiation impinging on the intervening cloud, the thermal and density structure, the elemental deuterium abundance and the rate at which cosmic rays induce ionization in the cloud. A large body of work on the relevant quantum processes, begun in the late 1960s by Alex and collaborators, underpins the construction of models like that of Black and Dalgarno. Some of the work on processes is described later. Alex had to possess a profound long term vision to construct the foundations upon which the models were built and then to develop and apply the models.

Knowledge of the elemental deuterium abundances in different regions constrains cosmological models and provides insight into the effect of astration on elemental abundances. Studies of the spatial variation of the cosmic ray induced ionization rate are relevant to the understanding of the acceleration and propagation of cosmic rays. Some of Alex’s additional findings on deuterium and cosmic rays in diffuse clouds are described in papers by Black and Dalgarno and Hartquist, Black and Dalgarno.

The abundance ratios of some deuterated species, including DCO$^+$, relative to their protonated counterparts, serve as diagnostics of the fractional ionization in dark molecular clouds. As described more fully later, the fractional ionization governs the role of the magnetic field in star formation.
in a dark cloud. Dalgarno and Lepp showed that in dark clouds sufficient deuterium is in atomic form to affect the deuterium fractionation. The inference of reliable constraints on fractional ionizations in dark clouds from observations of deuterated and protonated isomers requires consideration of key reactions involving atomic deuterium.

The interaction of cosmic rays with H$_2$ in interstellar clouds deposits energy and induces excitation. In the Jovian atmosphere, the energy deposition and excitation due to particles accelerated in the solar wind-magnetosphere interaction results in observable H$_2$ ultraviolet emission. Alex’s work on the interpretation of Jovian auroral and airglow emissions demonstrated the presence of substantial temperature gradients. We refrain from mentioning other Solar System related studies conducted by Alex, as others writing articles for this volume are addressing those topics. However, a mention of the Jovian work here is appropriate because the approach Alex took in it bears a relationship to that he adopted in some investigations of deposition in extra-Solar System objects, including SN1987A.

Monitoring of the SN1987A supernova ejecta revealed the presence of CO infrared line emission at 112 days. Liu, Dalgarno and Lepp developed a model of the thermal balance and chemistry of the ejecta. Heating is due to radioactive decays which produce $\gamma$-rays, and their interaction with matter generates energetic electrons. Radiative association forms CO. The very significant conclusion drawn about the ejecta’s dynamics is that microscopic mixing of helium-rich layers with layers rich in carbon and oxygen had to be at most very limited, despite the full development of the Rayleigh-Taylor instability during the explosion. Otherwise, microscopic mixing would have led to the destruction of CO by He$^+$ at a rate incompatible with the observations.

3. Others’ Work on Diagnostics

Studies of cosmic ray ionization rates continue. Observations of H$_3^+$ infrared absorption now provide constraints on the rates which imply they are an order of magnitude higher in some diffuse interstellar clouds than inferred by Alex and his collaborators in the 1970s. The differences are due to the adoption in the 1970s of a value for the H$_3^+$ dissociative recombination rate coefficient that is small compared to that now accepted. (See section 7 for a mention of the relevant experimental measurements.) The analysis by Caselli et al. of millimeter observations of deuterated species and their protonated counterparts has advanced our knowledge of the variation of the fractional ionization in dense molecular cores which are evolving to
form stars.

The inference of the dynamics of dense core collapse from millimeter and submillimeter molecular line observations is a very challenging problem. Given that the relative roles of hydromagnetic wave processes and gravity at different stages of collapse continue to be debated, that problem is important. Its solution requires the construction of appropriate dynamical models, the development of accurate models for the gas phase and surface chemistries of dense cores, and involved radiative transfer calculations. Data for multiple lines of multiple species are required. For a simple dynamical description, Tsamis et al.\textsuperscript{14} have performed relevant chemical and radiative transfer calculations. Much work remains, but their study gives a good indication of what is required.

The angular resolution and sensitivity of ALMA will enable the mapping of molecular distributions in protoplanetary discs. The study of the chemistry of the discs is at an early stage, and a full understanding of what can be learned about disc dynamics from molecular observations does not exist. Ilgner et al.\textsuperscript{15} are amongst those who have begun to address this issue by considering chemistry for an α disc model. The use of more complicated models of disc dynamics, including gravitational instability and the effects that the magnetic rotational instability has on viscosity, would be interesting. Thi, van Zadelhoff and van Dishoeck\textsuperscript{16} performed a notable observational study of simple organic molecules in protoplanetary discs around T-Tauri and Herbig Ae stars with single dish millimeter and submillimeter telescopes. Lahuis et al.\textsuperscript{17} detected emission from hot organic molecules in a protoplanetary disc with the Spitzer Space Telescope. From data obtained for the disc of TW Hydrae with the Submillimeter Array, Qi et al.\textsuperscript{18} have concluded that disc chemical models should include active deuterium fractionation. Existing results point to an interesting future for the diagnosis of protoplanetary discs with molecular observations.

4. Alex’s Work on Chemical and Quantum Control

Though this article primarily concerns molecular astrophysics, some of Alex’s contributions to astrophysics that did not address only molecules are too significant to exclude. The Dalgarno and McCray\textsuperscript{19} paper is known to astrophysicists working on a wide variety of nonmolecular sources including supernova remnants. Its title \textit{Heating and Ionization of HI Regions} is a bit deceptive. HI regions are the main topic of the paper, but the cooling of gas at temperatures far higher than those of HI regions is also addressed in it. Its famous Figure 2 shows the cooling rate coefficient for gas from tem-
Dalgarno and McCray\textsuperscript{19} considered molecular coolants but atomic processes received more space than molecular processes. They also summarized research initiated by themselves and C. Bottcher and M. Jura. Bottcher \textit{et al.}\textsuperscript{20} showed that supernovae and temporal variations in the population of hot stars are frequent enough that they prevent the interstellar medium from reaching a state in which gas is in two coexisting phases in pressure, ionization and thermal equilibrium. Later in the 1970s, the role of supernovae in establishing the global properties of the interstellar medium became a major topic in interstellar research. Alex and his collaborators pioneered the investigation of this important aspect of galactic astronomy.

Alex’s work on heating and cooling has extended to the molecular cooling of the Early Universe. Stancil, Lepp and Dalgarno\textsuperscript{21} examined the deuterium chemistry of the pregalactic and protogalactic eras. Though much less abundant than H\textsubscript{2}, HD was possibly an important coolant then, due in part to its possession of a dipole moment and H\textsubscript{2}’s lack of one. This difference between HD and H\textsubscript{2}, and the greater mass that D has than H has, leads to the lowest excited level of HD that can be populated by collisions with H having a roughly four times lower energy than the lowest excited level of H\textsubscript{2} that can be populated by collisions with H. Thus, as the temperature drops, HD becomes an increasingly more effective coolant than H\textsubscript{2}. HD’s dipole moment causes the radiative decay rates of its excited levels to be much larger than those of the corresponding H\textsubscript{2} levels. Consequently, the cooling rate per HD molecule continues to increase with increasing H number density to a higher density than the cooling rate per H\textsubscript{2} molecule does.

Lepp and Dalgarno\textsuperscript{22} performed early work on the role that photoabsorption by large molecules or large molecular ions (e.g., free flying polycyclic aromatic hydrocarbons and their negative ions) play in heating interstellar clouds. At the time of their work grain photoelectric heating had been advocated as the primary heating mechanism in diffuse clouds, but it was appearing to be insufficient in at least some sources. Lepp and Dalgarno\textsuperscript{22} identified photodetachment from large negative molecular ions as an important previously unconsidered heating process.

Section 2 contains a mention of the relevance of the fractional ionization to the part that magnetic fields have in molecular cloud dynamical evolution and star formation. Oppenheimer and Dalgarno\textsuperscript{23} developed a model of the chemistry governing the fractional ionisation in dark molecular regions. One of their key realizations is that charge transfer of molecular ions with neutral...
metal atoms causes a significant reduction in the gas phase recombination rate.

Star forming regions contain shocks driven by the winds and jets of young stars. In many cases these shocks may greatly influence subsequent star formation. In the second half of the 1970s and during the 1980s, the study of the shocks through the observation of infrared H$_2$ line emission at about 2 microns and of millimeter line emission from other molecules became a major industry. The theoretical models of the shocks had to increase in sophistication to match observational progress. Multifluid hydromagnetic models were developed. Draine, Roberge and Dalgarno\textsuperscript{24} contributed significantly in this area by constructing such models and by critically evaluating and compiling data for the processes controlling the thermal balance. The chemistry controlling the ionization balance has a major impact on the shock structure, because the size of the dissipation region depends on the number density of ions. In the paper by Pineau des Forêts \textit{et al.}\textsuperscript{25} Alex identified the chemistry controlling the ionization structure of shocks in diffuse clouds.

Alex's studies of how chemistry controls the thermal balance of astrophysical sources has included the work in which he explained the existence of large inhomogeneities in the thermal structure of the SN1987A ejecta as the consequence of the variation of the chemical structure throughout the oxygen core.\textsuperscript{26}

5. Others’ Work on Chemical and Quantum Control

During the 1980s and 1990s T. Ch. Mouschovias and his collaborators, F. H. Shu and his collaborators and others developed a picture of the birth of solar-mass stars in dense molecular cores undergoing gravitationally induced, quasistatic collapse regulated by the magnetic field and ambipolar diffusion. Ambipolar diffusion is the motion of charged species relative to neutrals driven by the magnetic force. In this picture the core forms with a magnetic flux to mass ratio that is too large for gravitationally induced collapse to proceed to higher densities if the flux to mass ratio does not alter. The core is said to be magnetically subcritical. However, due to the low fractional ionization, ambipolar diffusion occurs and reduces the magnetic flux, allowing low Alfvénic Mach number collapse. The ambipolar diffusion timescale depends on the number density of ions, which is the prime reason for the earlier mentions in this article of the fractional ionization in dense clouds.

In the late 1990s, the picture described in the previous paragraph was
challenged. For instance, Myers and Lazarian\textsuperscript{27} introduced a "turbulent cooling flow" description of the formation and evolution of dense cores. They wished to account for the observed linewidths of features arising in the envelopes of cores being broader than expected from some magnetic and ambipolar diffusion regulated gravitationally induced collapse models.

Ward-Thompson \textit{et al.}\textsuperscript{28} have summarized the issues in the debate about the roles of waves and of ambipolar diffusion operating with gravity in the birth of solar-mass stars. (We shall refer to waves rather than turbulence, which is a misnomer because the energy input scale and dissipation scale do not differ sufficiently for turbulence to develop fully.) Good evidence for wave induced evolution exists. However, good evidence for phases during which ambipolar diffusion and gravity operate together also exists (e. g. Chiang \textit{et al.}\textsuperscript{29}).

The simulations of Tassis and Mouschovias\textsuperscript{30} are representative of work by the Illinois group on dynamics showing the important role that the fractional ionization and charged grains play in the gravitationally induced, ambipolar diffusion regulated collapse phase. The simulations are of thin discs in which the structures vertical to the symmetry planes are in magnetostatic equilibrium.

Van Loo, Falle and Hartquist\textsuperscript{31} have demonstrated the importance of ambipolar diffusion and, hence, of the chemistry controlling the fractional ionization during the initial formation of dense cores by the nonlinear steepening of hydromagnetic waves. The relative roles of wave processes and gravitationally induced, magnetically regulated collapse at different phases of core evolution may be worthy of debate. In contrast, the fact that the chemistry controlling the fractional ionization is of great importance in core evolution is very clear.

Multifluid models of shocks in dark regions having hydrogen number densities exceeding about $10^5$ cm$^{-3}$ advanced in complexity during the 1990s, and only now are we on the verge of constructing reliable models of such shocks. The very important Draine \textit{et al.}\textsuperscript{24} work concerned shocks that are propagating perpendicularly to the magnetic fields. Of course, real shocks propagate obliquely to the magnetic fields. In dense regions, the collisions of neutrals with charged grains rather than the collisions of neutrals with ions dominate the coupling of neutral flows to magnetic fields. Draine \textit{et al.}\textsuperscript{24} treated the effects due to charged grains in an approximate fashion that is suitable for a wide variety of parameters but is not reliable for regions with number densities above above about $10^5$ cm$^{-3}$. Pilipp and Hartquist\textsuperscript{32} and Wardle\textsuperscript{33} initiated efforts to include charged grains more
Fig. 1. The rotation of the magnetic field within the shock front of C-type shock. The shock is propagating through a quiescent medium of $n_H = 10^6$ cm$^{-3}$ and $B_0 = 10^{-3}$G at 25 km s$^{-1}$. The angle between the shock propagation and the upstream magnetic field is $45^\circ$. The crosses represent the grid spacing of the numerical model.

rigorously in models of oblique shocks.

Wardle$^{33}$ showed that an attempt to solve the time-independent coupled ordinary differential equations governing steady plane-parallel shock structures through the integration in a downstream direction from upstream boundary conditions cannot yield solutions for fast-mode shocks. Rather integration has to proceed in the upstream direction from downstream conditions. This is not possible unless equilibrium conditions obtain at all points in the flow. Unfortunately, they do not. For instance, the abundance of H$_2$O, which is an important coolant, does not attain its equilibrium value as gas cools from several hundred degrees until it has been at about 10K for of the order of $10^5$ years or more. This is much longer than the flow time through a shock in a dark dense core. Consequently, a time-dependent approach is necessary. Such an approach including all electric current components in a proper fashion$^{34}$ has been combined only recently with a self-consistent treatment of the chemistry controlling the fractional ionization and grain charges and, hence, the coupling between neutral flow and the magnetic
field. Figure 1 shows the rotation of the magnetic field within the shock front of a steady C-type shock. The spiral node upstream is one of the reasons why Wardle needed to integrate the steady-state equations in an upstream direction to find a steady fast-mode shock.

Chemistry plays a huge role in controlling the mass loss from highly evolved stars. Ferrarotti and Gail conducted a comprehensive theoretical study of the formation of dust in Asymptotic Giant Branch (AGB) stars. Radiation pressure on the dust greatly influences the mass loss rates and terminal speeds of the outflows. Mass loss rates affect the stellar evolution and the nucleosynthesis products.

6. Alex’s Work on Quantum Processes Relevant to Astrophysics

Alex’s contributions to the study of processes important for the diagnosis and evolution of astrophysical sources are vast.

The volume of just his work on radiative processes important for modelling diffuse clouds is impressive. This includes the calculation of radiative probabilities for the Lyman and Werner bands of H$_2$. These are important for photodissociation and the pumping of excited rovibrational levels of ground electronic state of H$_2$. Turner, Kirby-Docken and Dalgarno computed H$_2$ ground electronic state rovibrational transition probabilities that help determine the level populations resulting from the cascade following pumping. They are also important for radiative cooling in shocked molecular gas in star forming regions. Other work on radiative mechanisms important in diffuse clouds includes that of van Dishoeck, van Hemert and Dalgarno who calculated the OH photodissociation rate.

Collisional processes are also important for H$_2$ level populations in diffuse clouds. Dalgarno, Black and Weisheit identified the role of H$_2$ collisions with H$^+$ in establishing the H$_2$ ortho-para ratio in diffuse clouds. They also identified H$_2$ collisions with D$^+$ as the dominant mechanism for forming HD in diffuse clouds.

The work of Chu and Dalgarno on collisional excitation of CO is relevant to the cooling and observational diagnosis of most detectable diffuse molecular material in the Universe. The adoption by Roberge and Dalgarno of a master equation approach for the calculation of the populations of rovibrational levels of H$_2$ in shocked gas led to a major advance in the understanding of the collisional dissociation of astrophysical molecules.

Alex has contributed many important studies of charge transfer processes of which that by Butler, Heil and Dalgarno is a good example. The
efforts of this trio at the end of the 1970s and the start of the 1980s had a huge impact on models of photoionized regions from planetary nebulae to the broad emission line regions of quasistellar objects. Their work led to the understanding of how charge transfer greatly influences the emission spectra of such plasmas. Of course, Alex’s more recent investigations, described elsewhere in this volume, of charge transfer have had major significance for research on the heliosphere, planetary atmospheres, comets and the interstellar soft X-ray background.

Supernova ejecta belong to the long list of different classes of astrophysical sources for which his investigation of quantum processes are relevant. For instance, Dalgarno, Du and You\textsuperscript{45} calculated the rates of the radiative association of O with C and C\textsuperscript{+} as part of Alex’s program on molecules in the ejecta of SN1987A.

7. Others’ Work on Quantum Processes Relevant to Astrophysics

The advance of molecular astrophysics has relied on many laboratory efforts involving a wide variety of techniques to obtain reliable reaction rate coefficients for temperatures ranging from about 10K to over 10\textsuperscript{3}K. For over two decades CRESU devices, in which expansion in supersonic jets cools gas, have facilitated low temperature measurements relevant for the chemistry of star forming regions. Though presented in the context of work on Titan’s atmosphere, the results obtained by Berteloite \textit{et al.}\textsuperscript{46} for C\textsubscript{4}H reactions with hydrocarbons provide recent examples of the type of data relevant for star forming regions that can be obtained with CRESU devices.

Storage ring experiments have produced a smaller volume of data relevant to astrophysics, but in some cases the storage ring results have had considerable impact. The measurement of the H\textsubscript{3}\textsuperscript{+} dissociative recombination rate by McCall \textit{et al.}\textsuperscript{47} has been important for the inference of cosmic ray ionization rates in diffuse clouds from observations of H\textsubscript{3}\textsuperscript{+}, which we mentioned earlier.

The original masthead of \textit{The Astrophysical Journal} described it as \textit{An International Review of Spectroscopy and Astronomical Physics}. Spectroscopy plays a key role in molecular astrophysics just as it does in other areas of astrophysics. An excellent example of the importance of laboratory molecular spectroscopy for astrophysics is provided by the work done by McCarthy \textit{et al.}\textsuperscript{48} which led to the first detection of an astrophysical negative molecular ion. C\textsubscript{6}H\textsuperscript{−} exists in the stellar envelope of IRC +10216 and in the dense molecular cloud TMC-1.
Theoretical calculations of line wavelengths and radiative transition rates for H$_2$O$^{19}$ made possible the first detection of water in the atmosphere of an extrasolar planet.\textsuperscript{50} Theoretical line list calculations (e.g. Harris \textit{et al.}\textsuperscript{51}) are important for work on the atmospheres of cool stars and low metallicity stars and distinguishing brown dwarves from planets.

To this point we have mentioned only gas phase processes. In the past decade the effort to understand grain surface processes affecting astrophysical chemistry has intensified. A key problem concerning the kinetics of interstellar grain surface reactions arises because the number of reactant atoms and molecules on a surface is often too small for a standard rate equation treatment to be appropriate. Caselli, Hasegawa and Herbst\textsuperscript{52} introduced a modified rate equation approach, which they have subsequently improved. Their 1998 paper triggered a considerable amount of research on how to treat interstellar grain surface chemistry. Green \textit{et al.}\textsuperscript{53} adopted a master equation approach with which they calculated the probabilities that a grain contains specific numbers of atoms and molecules of the different reactant species. The method is suitable for some simple problems but is too computationally expensive for many of interest. Barzel and Biham\textsuperscript{54} have developed a technique based on the use of equations they obtained by taking moments of the master equation. It shows considerable promise because it has proven accurate in test calculations and computationally tractable for problems involving many reactant species.

Laboratory studies of surface processes important for astrochemistry have included investigations of H$_2$ formation and desorption of ices. The short but informative review by Williams \textit{et al.}\textsuperscript{55} provides a good introduction to some of the research. While they made a good attempt to note work done elsewhere, the main focus of the Williams \textit{et al.}\textsuperscript{55} review is research carried out by several UK groups. Several excellent surface chemistry groups exist throughout the world. The Leiden group is one. Recent work in that group has included a study of the photodesorption of CO ice.\textsuperscript{56}

The formation of astrophysical dust in carbon-rich stellar envelopes is better understood than its production in oxygen-rich envelopes. Uncertainties in the field are sufficient that Nuth and Ferguson\textsuperscript{57} felt moved to proclaim, in the title of a paper on their relevant experimental results, that \textit{Silicates Do Nucleate in Oxygen-Rich Circumstellar Outflows} ... Astronomical observations had already established this fact, but the problem of explaining it has been so challenging that Nuth and Ferguson\textsuperscript{57} had some grounds for announcing their progress in the manner they did. Theoretical efforts to identify the species important in the nucleation of astrophysical
dust involve the development and application of methods to evaluate the energies of multiple configurations of various numbers of particles of the nucleating species. Bhatt and Ford\textsuperscript{58} have recently published theoretical results on the investigation of MgO as a possible nucleating species around M stars.

8. Closing Remarks

The unusually lengthy list of keywords at the start of this article reflects the broad range of the work that Alex has done in astronomy and the breadth of its impact.

One does not need to possess great prognostic powers to know that molecular astrophysics has a bright future. Herschel is due to be launched in 2009 and ALMA will be operational well before Alex turns 90. When we meet to celebrate that occasion, we will have learned a lot more about astrophysical molecular sources through the use of those two facilities.

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