Young intermediate-mass stars: from a HIFI spectral survey to the physics of the disk inner rim
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The subject of this thesis is the birth of stars, and of the planets around them. Work in these areas can help us to better understand the origin of the myriad stars and planets in the Universe, but also of our own Sun, Earth and selves, as well as to estimate the probability of finding similar abodes for life elsewhere.

Specifically, I have studied the microwave spectrum of a star-forming gas clump, revealing the complexity of its chemical and physical structure in Chapter 2 and studying the properties of its most extreme components in Chapters 3 and 4. Moving on through star and planet formation, in Chapter 5 I have presented a theoretical and numerical study of the hottest dusty regions in planet-forming disks around young stars, revealing the great diversity of possible dust distributions and elucidating general principles in models of such systems.

The formation of stars and planets

Giant complexes of molecular gas clouds, stretching through space for tens or hundreds of light-years, are the nurseries in which new stars are formed. Chaotic motions that are constantly generated in such clouds by large-scale gas flows, supernova explosions and other mechanisms cause them to have variations in density. Some of these variations are large enough for self-gravity to make them stable against thermal expansion and other dissipative forces. Such a bound core slowly contracts, forming a central dense object onto which material is fed through an accretion disk. The central object grows until the pressure at the centre becomes sufficient to make it possible for hydrogen nuclei to fuse together, forming helium and releasing energy. A star is born.

The freshly minted star heats the inner part of its surrounding envelope, leading to an increase in thermal infrared radiation and, because many higher rotational energy levels can now be populated, in molecular line emission. The extended envelope of colder gas around the protostar hides the star from view in visible light.

As starbirth occurs in material with random large-scale motions and angular momentum is conserved in collapse, the forming object will generally be rotating. It is easier to collapse along the rotation axis, so the gas around the newborn star flattens into a spinning disk. Over tens of thousands of years, an outflow of gas along the
rotation axis dissipates what remains of the envelope, and the star becomes visible. Within the protoplanetary disk (see Fig. S.2) around it, dust grains – the microscopic mineral particles that are present everywhere in interstellar gas – undergo collisional growth, which over millions of years leads to the formation of rocky planets.

The chemistry of star formation

As the temperature and density structure, as well as the motions, of a collapsing gas cloud evolve, so does its chemical composition. For example, where the gas is very cold, many atoms and molecules freeze onto the dust grains, where they can carry out reactions that are not possible in the gas phase. Other processes can only occur at high temperatures. For example, in the inner envelope, which is heated by the protostar, chemical species frozen onto or formed on dust grains can evaporate and participate in the gas-phase chemistry. Shockwaves originating in the outflow from the protostar sputter atoms from the dust into the gas, and also heat the gas, one result being the efficient formation of water. Thus, the chemical makeup of a star-forming gas clump represents the diversity of physical conditions and processing histories of its different parts.

Molecular hydrogen is the dominant gas species in star-forming regions. It is followed by carbon monoxide, which is 10 000 to 100 000 times less abundant. However, due to a lack of dipole moment H₂ itself cannot usually be seen in the relatively cool gas from which stars form, while the rotational transitions of CO are easily ob-
Figure S.2: Left panel: The OMC-2 region, a part of the Orion stellar nursery shown in Fig. S.1. Newborn stars intermingle with their still growing yellowish and reddish counterparts. Wisps of interstellar material are visible diagonally across the image. Also seen are several outflows and the shadow of an edge-on disk system. OMC-2 FIR 4, the protostar studied in this thesis, is below centre. Credits: UKIRT/JAC. Right panel: A protoplanetary disk seen as a dark silhouette against extended glowing gas in Orion. The disk of planet-forming material is edge-on, the glow of its central star is visible below the centre of the disk. Credits: J. Bally (University of Colorado) and H. Throop (SWRI).

servable at microwave wavelengths. Most other molecules are at least 100 times less abundant than CO, but many are still detectable due to strong transitions in the microwave regime. These include the commonly seen CS, HCN and methanol, as well as deuterated isotopologues of various species.

Spectral lines as diagnostic tools

Molecules can be in various discrete energetic states. The states relevant to this thesis are the rotational energy levels. When a particle spontaneously transitions from a higher energy rotational state to a lower one, a photon is emitted to carry away the energy and angular momentum difference. The set of energy levels and their differences is unique to a given molecule and thus each has its own spectral fingerprint. Furthermore, the fraction of particles of a given species that are in a specific state, and thus able to emit at a particular frequency, is a function of ambient conditions such as the density and temperature of the gas. A line spectrum of a volume of gas is a tracer of its composition and properties.

The combined radiation from dozens of relatively abundant molecules, and the diversity of physical conditions which allows to excite both low- and high-lying energy levels, leads to protostellar cores having very rich and informative microwave
Figure S.3: A small segment of the broadband microwave spectrum of OMC-2 analyzed in Chapters 2, 3 and 4 of this thesis. Several emission lines – mostly transitions of methanol, with a single CS line at 832.057 GHz – and a CH$^+$ absorption line are visible. Even this short spectrum provides information about the chemical composition of the star-forming gas and the detection of multiple transitions of methanol allows to determine other properties, such as density and temperature.

**This thesis**

Many molecular spectral lines are difficult or impossible to observe from the surface of the earth due to strong infrared absorption in the atmosphere. Recently, the HIFI spectrometer on the European Space Agency’s *Herschel Space Observatory* has given us access to an unprecedented combination of frequency coverage, spectral resolution and sensitivity, including a large range of frequencies entirely impossible to see with ground-based instruments. Among other things, for the first time, the higher rotational transitions of many common molecules can be regularly observed in protostars. Several molecular hydrides and hydride ions are observable for the first time. Using...
these capabilities, the CHESS Key Programme team aims to make one of the first comprehensive systematic comparisons of protostars at the terahertz frequencies observable with HIIF. The question is exploratory: how do the chemical composition and spectrum of protostars vary with mass, age and environment?

One of the most famous and nearby stellar nurseries is located fourteen hundred light years away, in the direction of the Orion constellation. Thousands of stars are forming in this cloud complex, a part of which is shown in Fig. S.1. A zoom-in of the region around the protostellar core OMC-2 FIR 4, one of the objects in the CHESS programme, is shown in the left panel of Fig. S.2. This young object, an unremarkable dark patch below the image centre, is the focus of Chapters 2 through 4.

In Chapter 2, I present and characterize the Herschel/HIFI spectrum of OMC-2 FIR 4, 0.4% of which is shown in Fig. S.3. This dataset is the first full spectrum of an intermediate-mass protostar (meaning it will form a star of a few solar masses) in the terahertz frequency regime and contains more than seven hundred lines from 41 chemical species. The diversity of species, transitions and line profiles detected reveals a new level of complexity of the structure, chemistry and kinematics of the source, that we are only beginning to understand. Based on their profiles, the detected chemical species trace at least four different, and mostly new, kinematical and physical components.

In Chapter 3, a hundred-strong subset of methanol lines from the HIFI survey of OMC-2 FIR 4 is analyzed, revealing a compact, hot, Solar System sized central region within the the large-scale, cold protostellar envelope. This is likely the hot core, directly heated by the newly formed protostar.

In Chapter 4, I present a study of the high-velocity wings of H$_2$O and CO emission lines observed towards OMC-2 FIR 4. The emission is found to originate in very compact, water-rich regions of similar size to the hot component presented in Chapter 3 and consistent in its properties with gas processed by strong shockwaves. The analysis strongly suggests the presence of a previously unseen compact outflow from the protostar.

In Chapter 5, I describe the modeling of the innermost regions of planet-forming disks – such as that shown in the right panel of Fig. S.2 – around stars in their late phases of formation, finding a range of possible distributions of the microscopic mineral grains that will grow into planets and giving a generally applicable analytical description of the numerical results.

**Outlook**

The rich HIFI spectrum of OMC-2 FIR 4 is allowing us to characterize this protostellar core in unprecedented detail and is providing evidence for a central hot core, a compact outflow, and further substructure of an unclear nature. The stage is set for further detailed analyses and for comparisons with other protostars. We expect a wealth of discoveries and new questions to emerge from this work in the coming few years. Targeted follow-up observations of selected molecules with high spatial resolution interferometers, such as ALMA, will be a key point in testing the nature of the substructure found in OMC-2 FIR 4 with HIFI.