Saas-Fee Advanced Course 42
Swiss Society for Astrophysics and Astronomy

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Dynamics of Young Star Clusters and Associations

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Edited by Cameron P.M. Bell, Laurent Eyer
and Michael R. Meyer

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This Series is edited on behalf of the Swiss Society for Astrophysics and Astronomy: Société Suisse d'Astrophysique et d'Astronomie Observatoire de Genève, ch. des Maillettes 51, CH-1290 Sauverny, Switzerland

Cover illustration: The Orion Nebula Cluster, hosting several thousand stars and substellar objects, is the richest aggregate of young stars within 1500 light years (about 500 parsecs), and can be found within the 'sword' region of its eponymous constellation. CREDIT: NASA, ESA, M. Robberto (Space Telescope Science Institute/ESA) and the Hubble Space Telescope Orion Treasury Project Team.

ISSN 1861-7980 ISSN 1861-8227 (electronic)
Saas-Fee Advanced Course
ISBN 978-3-662-47289-7 ISBN 978-3-662-47290-3 (eBook)
DOI 10.1007/978-3-662-47290-3

Library of Congress Control Number: 2015946088

Springer Heidelberg New York Dordrecht London

Printed on acid-free paper

Springer-Verlag GmbH Berlin Heidelberg is part of Springer Science+Business Media
(www.springer.com)

Foreword

The Saas-Fee schools are legendary and I vividly remember the one I attended as a second-year graduate student, exactly 30 years before this one, entitled: “Morphology and Dynamics of Galaxies”. This year’s topic is very timely, as the study of the dynamics of young stellar clusters and associations will get an enormous observational boost from the *Gaia* mission and the many ongoing spectroscopic programmes, including those on ESO’s telescopes. Adriaan Blaauw (1914–2010) pioneered this field in the 1940s and 1950s, and young star clusters and associations continued to have his interest throughout his entire life. I was privileged to carry out a small student project with him which much later, but by now more than 15 years ago, led to the *Hipparcos* census of the nearby associations and follow-up work on the run-away OB stars, in both of which Blaauw had an active role. Since then the field has moved forward again, and the lectures by Cathie Clarke, Bob Mathieu and I. Neill Reid provide an excellent overview of the state of the field, with an exciting glimpse of the future.

Tim de Zeeuw

Preface

Where do most stars (and the planetary systems that surround them) in the Milky Way form? What determines whether a young star cluster remains bound (such as an open or globular cluster), or disperses to join the field stars in the disc of the galaxy? These questions not only impact understanding of the origins of stars and planetary systems like our own (and the potential for life to emerge that they represent), but also galaxy formation and evolution, and ultimately the story of star formation over cosmic time in the Universe.

To help young (and older) scientists understand our current views concerning the answers to these questions as well as frame new questions that will be answered by the European Space Agency's *Gaia* satellite that was launched in late 2013, we proposed the 42nd Saas-Fee Advanced Course "Dynamics of Young Star Clusters and Associations" to the Swiss Society of Astronomy and Astrophysics in October, 2010. The course was approved and we began to organise the school. The lectures were held in the alpine village of Villars-sur-Ollon in March 2012. We were very fortunate to have such world renowned experts agree to participate as lecturers, including Cathie Clarke (University of Cambridge) who presents the theory of star formation and dynamical evolution of stellar systems, Robert Mathieu (University of Wisconsin) who discusses the kinematics of star clusters and associations, and I. Neill Reid (Space Telescope Science Institute) who provides an overview of the stellar populations in the Milky Way and speculates on from whence came the Sun. We also benefitted from the participation of Dr. Timo Prusti (ESA) who presented a special lecture on the expected performance and impact of the *Gaia* satellite (material presented in that lecture can be found at https://cast.switch.ch/vod/clips/29ksi0s1o8/link_box and is not part of this book). Although Prof. Tim de Zeeuw was not able to participate in the school, we are grateful for his thoughtful words that grace the preceding page of this volume.

In March 2012, over 60 Ph.D. students, post-doctoral fellows and senior scientists of every career stage came to hear these lectures, think about the formation and evolution of star clusters, argue, discuss and learn (there was probably some skiing involved as well). We are grateful to each of the attendees for their active and enthusiastic participation in the school. As is often the case, the organisers and lecturers learnt as much from them as the students did from us. Each lecturer presented seven individual lectures, and a few combined lecture/discussions were also held. We also provided electronic transcripts of the lectures to each author as an aid in preparing this written version. In this volume we attempt to capture most of the material presented. Each of the lecturers of course has a unique style, as well as associated strengths and weaknesses in the presentations. We have tried to preserve those, while also injecting some uniformity of content and format. If you wish to review our work, you may view the lectures online at http://www.astro.phys.ethz.ch/sf2012/index.php?id=videos-slides.

Of course with any undertaking such as this, there are many people to thank. Ms. Marianne Chiesi (ETH) is chief among them. She was crucial to the organisation of the school, was on-site during the week of the event, and played a critical role afterwards in helping us get organised to produce this volume. We also thank Ms. Myriam Burgener from the University of Geneva for providing very helpful organisational advice in the lead up to the school. The local organising committee consisted of Dr. Richard Parker, Ms. Maddalena Reggiani, Mr. Michiel Cottaar, Dr. Richard I. Anderson and Mr. Lovro Palaversa. In particular, Dr. Richard Anderson and Lovro Palaversa were instrumental in helping to record the lectures for online access and transcription. The staff of the Eurotel Victoria Villars Hotel was very helpful, friendly, and accommodating to our needs. We also thank the Community of Villars-sur-Ollon for helping us to arrange some social events (at discount) for the participants of the school. Finally, we would also like to thank our colleagues at Springer, in particular Mr. Ramon Khanna and Ms. Charlotte Fladt, for their patience and support throughout this process.

One of us (MRM) would like to also express his gratitude to his colleagues, Dr. Cameron Bell and Dr. Laurent Eyer, for their dedicated effort, and unwavering support throughout this editorial process. In particular, Cameron Bell, who joined our efforts after the school was completed, deserves all possible recognition and accolade for his hard work in completing this volume as lead editor. Without him, this book would never have been published. However, for any errors that remain, despite our best efforts to catch them, we take full responsibility.

ETH Zürich — Michael R. Meyer
Observatoire de Genève — Laurent Eyer

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Part I
Theory of Star Formation and Dynamical Evolution of Stellar Systems

Chapter 1
The Raw Material of Cluster Formation: Observational Constraints

Cathie J. Clarke

Star clusters form from reservoirs of dense cold gas ('Giant Molecular Clouds', henceforth GMCs) and in the following chapters we explore the wealth of recent simulations that follow this process, together with simulations that model the later (essentially gas-free) evolution of clusters.

A first step in any simulation is to decide on the initial conditions and for the cluster formation problem we need to specify the properties of GMCs (their typical densities and temperatures, levels of internal motions, homogeneity, etc.). We will mainly base these parameter choices on observational data and hence this chapter provides an overview of GMCs' observed properties. We will also use insights from larger scale (galaxy-wide) calculations in which GMCs emerge from simulations of the large scale interstellar medium (henceforth ISM). This brief overview is angled towards the kinds of issues that are relevant to understanding cluster formation and is no substitute for the kind of broader review of molecular clouds that can be found elsewhere: see for example Blitz (1991), Williams et al. (2000), McKee and Ostriker (2007), Fukui and Kawamura (2010), and Tan et al. (2013).

1.1 Overview of Molecular Cloud Observations

The total inventory of molecular gas in the Galaxy is estimated to be around 2.5×10^9 $M_\odot$, with about a third of the gas mass inward of the solar circle believed to be in molecular form (Wolfire et al. 2003); this number is somewhat uncertain because of the difficulty in detecting a possibly significant component in very cold gas (Loinard and Allen 1998). It is well known that molecular clouds are associated with spiral arms, both in the Milky Way (Heyer et al. 1998; Stark and Lee 2006) and in external galaxies (Helfer et al. 2003). This association is to be expected since spiral arms are

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C.P.M. Bell et al. (eds.), *Dynamics of Young Star Clusters and Associations*,
Saas-Fee Advanced Course 42, DOI 10.1007/978-3-662-47290-3_1

conspicuous in the blue light associated with young stars; since these stars have not had time to migrate far from their birth locations one would expect their natal gas to trace a similar pattern. The origin of the spiral pattern in the gas is believed to be the formation of shocks as the gas flow responds to the spiral pattern in the underlying mass distribution (Roberts 1969).

Stars form from molecular gas because the associated *Jeans mass* is low. The Jeans mass is the minimum mass required for gravitational collapse against support by pressure gradients and is given by:

$$M_{\rm J} = 0.2\,{\rm M}_\odot \left(\frac{T_{10}^3}{n_5}\right)^{1/2}, \tag{1.1}$$

where T_{10} is the temperature in units of 10 K and n_5 is the number density of hydrogen normalised to $10^5\,{\rm cm}^{-3}$ (which is typical of the densest regions within GMCs). The corresponding length scale ($r_{\rm J}$) is obtained by equating $M_{\rm J}$ with the mass contained within a sphere of radius $r_{\rm J}$ so that we obtain:

$$r_{\rm J} = 0.06\,{\rm pc}\left(\frac{T_{10}}{n_5}\right)^{1/2}. \tag{1.2}$$

A simple heuristic way of arriving at these scales is obtained by equating the timescales for free-fall collapse with the sound crossing timescale across a region. It is then unsurprising that cold and dense conditions (as found in GMCs) are associated with a low Jeans mass and a tendency towards gravitational collapse on small scales.

It is hard to assign meaningful 'average' properties to molecular clouds because of the hierarchical organisation of the ISM, consisting of nested structures on a large dynamic range of scales (see e.g. Scalo 1990; Elmegreen 2002). A plethora of terminology is used to describe local over-densities in terms of 'clumps' or 'cores' (Williams et al. 2000; Bergin and Tafalla 2007). We will discuss methods of characterising this hierarchy in Chap. 3 but for now there are a few numbers that are worth noting: molecular gas is organised into GMCs with typical masses in the range of a few $\times 10^5\,{\rm M}_\odot$ (these often being surrounded by atomic envelopes of similar mass; Blitz 1991). The mass distribution of GMCs is describable as a power-law with index -1.6 (Blitz et al. 2007), i.e. the fraction of clouds by number in a given mass range scales with cloud mass, $M_{\rm cl}$, as $M_{\rm cl}^{-1.6}$. This distribution is shallower (more mass on large scales) than the corresponding distribution for massive stars where the power-law index is -2.35 (Salpeter 1955). In the case of GMCs the power-law is however only defined over about an order of magnitude in mass since the largest GMCs in the Milky Way have masses slightly in excess of $10^6\,{\rm M}_\odot$ and the distribution is limited by completeness at the low mass end.

The mean column densities and mean volume densities of molecular clouds are of particular interest, being a little less than $\sim 10^{22}\,{\rm cm}^{-2}$ and $\sim 300\,{\rm cm}^{-3}$ respectively. We discuss below how the former quantity depends on how the cloud boundary is defined (see Lombardi et al. 2010). The typical column density is at least partly set by the requirement that clouds are dense enough to be self-shielded against photodissociation by the Galaxy's ambient ultraviolet radiation field (van Dishoeck and Black 1988). The mean density $\tilde{\rho}$ (which does not necessarily relate to a typical density of structures within clouds, given their clumpy structure, but is simply derived from the ratio of total mass to total volume) can be used to estimate a characteristic free-fall timescale through $t_{ff} \sim (G\tilde{\rho})^{-1/2}$: this turns out to be about a Myr. This number will be relevant to our later discussions about whether GMCs collapse and form stars on a free-fall timescale.

Before proceeding further with a description of the empirical 'laws' that are applied to the internal structure of GMCs we now set out a brief guide to the techniques that are used to measure the properties of molecular clouds.

1.2 Observational Techniques Applied to GMCs

GMCs are predominantly composed of molecular hydrogen: it is therefore highly inconvenient that this molecule has no permanent dipole moment since this limits the transitions corresponding to observable lines. Indeed the lowest pure rotational level of H_2 has an excitation temperature of 510 K, which is far higher than the temperatures of molecular clouds (typically 10 s of K away from regions of massive star formation). This problem has led to a number of other diagnostics being used as a *proxy* for H_2. Below we summarise the complementary information that can be gleaned from line emission, dust emission and dust absorption, and discuss the advantages and disadvantages of each technique.

1.2.1 Molecular Line Emission

Line emission from a variety of abundant molecules is used to study cloud structure and kinematics. Early surveys (Solomon et al. 1987) used the second most abundant molecule in GMCs (^{12}CO); molecular clouds are generally optically thick in this emission so that it does not provide a good measure of cloud *mass*. It is thus preferable to use lower abundance molecules that are optically thin up to higher overall column densities. One of the most commonly used tracers is ^{13}CO (see Heyer et al. 2009); other commonly used molecules instead trace the densest gas within molecular clouds (e.g. NH_3: Bergin and Tafalla 2007; Juvela et al. 2012; HCN: Gao and Solomon 2004; Wu et al. 2005 and CS: Plume et al. 1997; Shirley et al. 2003).

The most obvious benefit of using molecular line data in the present context is that it provides a unique diagnostic of cloud *kinematics* via Doppler shifted emission. It thus allows a determination of the dynamical state of GMCs and this will turn out to be very important information for initialising cluster formation simulations. Moreover, the use of transitions with different critical densities (i.e. densities at which collisional and radiative de-excitation rates are equal) provides information on *volume* densities, whereas dust emission/absorption only measures column densities. Finally, for those with an interest in the chemistry of molecular clouds, molecular emission spectra provide important diagnostic information (see the reviews of Bergin and Tafalla 2007; Caselli and Ceccarelli 2012), constraining for example the free electron abundance (e.g. Bergin et al. 1999; Caselli et al. 2002) and the ages of star-forming regions (Doty et al. 2006).

On the other hand, chemical considerations can be a complicating factor when it comes to deriving the column density of H_2 from the flux in a given spectral line. There is a considerable debate in the literature about whether one can use a global conversion factor between CO and H_2 (Solomon et al. 1997; Blitz et al. 2007; Tacconi et al. 2008; Liszt et al. 2010; Wolfire et al. 2010; Sandstrom et al. 2013); additionally at high densities there is the issue of depletion of molecular gas on to grains (Redman et al. 2002; Jørgensen et al. 2005) so that gas phase diagnostics do not necessarily relate straightforwardly to the total abundance levels.

1.2.2 Dust Emission

Another widely used diagnostic of molecular cloud structure is thermal emission from dust. In order to derive the column density of gas from the flux density of dust emission at a single wavelength (usually in the millimetre or sub-millimetre range) one needs to be confident in a number of assumptions. One needs to know the fractional abundance of dust grains (compared with hydrogen), the dust emissivity law and the temperature of the emitting material. In practice one does not usually know the temperature *a priori* and thus multi-wavelength data is used to constrain this. Mapping with the *Herschel* Far Infrared satellite at wavelengths of 70–500 μm has recently provided dust continuum measurements at shorter wavelengths and has proved valuable for improving temperature constraints (e.g. Könyves et al. 2010).

The great advantage of thermal dust emission measurements is that they can not only be used to survey entire clouds—since even relatively dense structures in molecular clouds are still optically thin at millimetre wavelengths—they also allow the mapping of the densest regions of GMCs known as ‘dense cores’ (e.g. Motte et al. 1998; Johnstone et al. 2000). The disadvantages (apart from the lack of kinematic information) relate to uncertainties in the relationship between dust emissivity and gas mass (deriving both from uncertainties in dust emission properties and the dust to gas ratio). Moreover, in the case where a telescope beam contains emission components at a range of temperatures the mapping between multiwavelength dust emission and the total dust column can be under-constrained by the data.

1.2.3 Dust Absorption

This last difficulty is circumvented in the case of dust absorption measurements. This is because the attenuation of background sources by intervening dust depends only on the dust opacity and absorption coefficients and not on the dust temperature. 'Extinction mapping' (e.g. Lombardi and Alves 2001; Lombardi et al. 2006) is based on measuring spatial variations in the distribution of infrared colours of background stars. By comparing this distribution with that in control fields 'off-cloud' such measurements can be used to deduce a column density map of the cloud (again with the above provisos about uncertainties in the dust opacities and dust to gas ratio). Deep near-infrared measurements mean that it is possible to penetrate large limiting column densities ($\sim 10^{23}$ cm^{-2}; Román-Zúñiga et al. 2010) and thus allow the mapping of dense cores; deep observations also improve the spatial resolution since they allow a denser sampling of the background stellar sources. Detailed comparison of maps obtained via continuum emission and via extinction mapping indicates fair agreement over all though with some differences (Bianchi et al. 2003; Goodman et al. 2009; Malinen et al. 2012).

1.3 Magnetic Support and the Star Formation Efficiency Problem

Following this summary of observational methods for measuring cloud masses and kinematics, we now consider the energy budget within clouds. It is well-established that the gravitational, kinetic and magnetic energies of GMCs are comparable in magnitude whereas their thermal energy is orders of magnitude smaller. (See below for a description of magnetic field measurements in molecular clouds). This hierarchy of energies immediately implies that GMCs are not (in contrast to stars) supported by thermal pressure and this has led to the view that clouds are supported by either turbulent motions or magnetic fields. There is however a problem with sustaining such support. As we have noted, clouds are highly clumped and since the kinetic energy densities are much higher than thermal energies this means that these clumps are in a state of highly supersonic motion. Collisions between clumps are expected to be highly dissipative and this should lead clouds to collapse on a free-fall time. At one time it was believed that this situation would be mitigated by magnetic fields (even if these fields were themselves insufficient to support a static cloud) since shocks are less dissipative if they are magnetically cushioned by fields in the plane of the shock. However, simulations of hydrodynamical and magneto-hydrodynamical (MHD) turbulence (Gammie and Ostriker 1996; Mac Low et al. 1998) demonstrated that magnetic fields do *not* increase the turbulent dissipation timescale (an effect that can be broadly understood from the fact that in a turbulent medium the fields are not always parallel to shock fronts).

On the other hand, magnetic fields of sufficient strength *can* impede cloud collapse even in the absence of internal cloud motions. The ability of magnetic fields to support a static cloud against gravitational collapse can be cast in terms of a critical mass-to-flux ratio (Mouschovias and Spitzer 1976). We can derive a heuristic estimate for this value (by analogy with our description of the Jeans mass above) by comparing the free-fall collapse time with the timescale for Alfven wave propagation: Alfven waves propagate through a magnetised medium at a speed of $(B^2/\mu_0\rho)^{1/2}$ (for magnetic flux density B, magnetic permeability μ_0 and density ρ) and represent an important dynamical communication mode in magnetised media. The result of this exercise is that the critical mass-to-flux ratio is simply given by a factor of order unity times $G^{-1/2}$. Note that the critical Jeans mass (see Eq. 1.1) depends on gas density and therefore this changes—if the initial mass exceeds the initial Jeans mass—as a cloud collapses; for magnetised clouds the critical mass-to-flux ratio is however constant. Thus—provided that the magnetic field remains 'frozen' to the gas (i.e. the mass-to-flux ratio is fixed)—the ratio of a cloud's mass-to-flux ratio to the critical value is itself constant. The extent to which a cloud is either subcritical or supercritical thus does not change during collapse. It was at one time widely assumed that magnetic fields are indeed sub-critical and thus non-ideal MHD effects (specifically ambipolar diffusion: Mestel and Spitzer 1956; Galli and Shu 1993; McKee et al. 1993) were invoked as a means to slowly increase the mass-to-flux ratio and hence modulate the rate of cloud collapse (and star formation).

Subsequently there has been considerable observational effort devoted to the measurement of magnetic fields in star-forming clouds. Although the morphology of the magnetic field in the plane of the sky can be inferred from dust polarisation measurements (e.g. Heiles 2000), its magnitude can only be estimated through Zeeman polarimetry on Zeeman sensitive lines such as OH, CN and HI. Such measurements however only measure the component of the magnetic field along the line-of-sight and thus needs to be assessed in a statistical sense from a large ensemble of measurements. Early studies (Crutcher 1999) indicated that the mass-to-flux ratios in molecular clouds were close to critical (i.e. confirming that the magnetic energy density was of comparable magnitude to the gravitational potential energy). A decade of further observations and analysis has led to the conclusion that the mass-to-flux ratio is roughly twice critical: Crutcher et al. (2010) noted that the Zeeman data was 'inconsistent with magnetic support against gravity' and noted that the observed scaling of magnetic field strength with density ($B \propto \rho^{2/3}$) was as expected if the magnetic field was being passively advected in a gravitationally dominated flow. This situation is in contrast to that in the diffuse (atomic) interstellar medium where magnetic fields are instead sub-critical (Heiles and Troland 2004) and the lack of correlation between magnetic field strength and density is indicative of magnetically dominated conditions.

Clearly, therefore, magnetic fields must be important in the process of GMC formation from the diffuse medium (Kim and Ostriker 2006; Mouschovias et al. 2009). Even on the scale of GMC interiors (which will form the subject of much of these chapters), the only mildly super-critical conditions mean that magnetic fields should *not* be ignored. It is worth emphasising that most of the simulations described below omit magnetic fields for purely practical reasons.

The above results have an important implication for what is often described as the 'star formation efficiency problem'. Given that hydrodynamical and MHD turbulence both dissipate on a free-fall time and given that magnetic fields are insufficient to prevent collapse, we are left to conclude that clouds should collapse on a free-fall timescale, unless there are mechanisms that re-inject energy into the turbulence. We might therefor expect—unless the formation of stars itself disperses the remaining gas—that the timescale on which a GMC is converted into stars is its free-fall time ($\sim$1 Myr). There are however a number of observational indications that this is *not* the case. If we divide the entire mass of molecular gas in the Milky Way ($\sim 10^9\,M_\odot$) by a typical cloud free-fall timescale, we would expect that the Galactic star formation rate would be $\sim 10^3\,M_\odot\,yr^{-1}$, which exceeds the observed rate by more than two orders of magnitude. We therefore conclude that the star formation rate associated with GMCs (averaged over the time that gas is within GMCs) is much less than the total mass in GMCs divided by the free-fall time.

This conclusion, based on galaxy-wide scales, has been confirmed by recent studies within individual GMCs. Probably the most comprehensive study to date is that of (Evans et al. 2009) which used the *Spitzer* 'Cores to Disks' Legacy Survey to compare the census of young stars with the magnitude of the available mass reservoir. The results of this exercise confirmed that star formation is indeed inefficient with around 3–6 % of the cloud mass being converted into stars per free-fall time.

1.4 Scaling Relations

Following the first large-scale surveys of the structure and kinematics of molecular clouds, several correlations ('scaling relations') were noted by Larson (1981). These are now known widely as 'Larson's Laws' and concern the inter-relationship between mass, linear size and velocity width for structures within molecular clouds:

1. The velocity dispersion σ across structures of different size (R) scales as $\sigma \propto R^{0.5}$ (see Solomon et al. 1987). Since this relation was derived from radio line observations it is often termed the 'size linewidth' relation: see Fig. 1.1.
2. The mass (M), R and σ are related by $M \sim R\sigma^2/G$.
3. The mean density varies inversely with R or (equivalently) different structures within clouds share a roughly constant column density: $M \propto R^2$. Note that a situation of constant column density cannot be true in detail or else there would be no contrast between different structures within clouds. Lombardi et al. (2010) have shown that extinction mapping (see Sect. 1.2.3) within several GMCs demonstrates that the distribution of column densities within a cloud is describable as a log normal. The mean column density within a cloud depends on the level at which the data is thresholded (i.e. what is the lower limit on extinction used to define the cloud boundary). Since the distribution of column densities appears to be rather similar from cloud to cloud, the mean column density is indeed similar in different clouds, provided the clouds are analysed above the same extinction contour.