Submillimetre wave astronomy

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CAMBRIDGE UNIVERSITY PRESS
Cambridge
London New York New Rochelle
Melbourne Sydney

Published by the Press Syndicate of the University of Cambridge
The Pitt Building, Trumpington Street, Cambridge CB2 1RP
32 East 57th Street, New York, NY 10022, USA
296 Beaconsfield Parade, Middle Park, Melbourne 3206, Australia

First published 1982

Printed in Great Britain at the University Press, Cambridge

Library of Congress catalogue card number: 82-4487

British Library Cataloguing in Publication Data

Submillimetre wave astronomy
1. Radioastronomy — Congresses
2. Submillimetre waves — Congresses
I. Beckman, J.E. II. Phillips, J.P.
522'.682 QB474

ISBN 0 521 24733 0

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About this book:

Submillimetre waves are an area of intense activity and interest in astronomy, lying between very high frequency radio waves and far infrared waves. Studies of far infrared radiation from cosmic sources are particularly valuable for investigating cool and hot molecular clouds in the Galaxy. It is in this part of the electromagnetic spectrum that one encounters an overlap of chemistry and astrophysics.

This book consists of selected contributions presented at the conference on submillimetre wave astronomy held at Queen Mary College, London, in September 1981. Separate sections deal with the large-scale structure of the Galaxy, submillimetre wave sources and their detection, the interaction between chemistry and astronomy, and instrumentation and techniques.

Submillimetre wave astronomy will be of great interest to astronomers, astrophysicists and professional workers in microwave and molecular-line astronomy.

This book is published from author-prepared camera ready copy. Final copy was received from the editors at the end of June 1982. The book was published September 1982.

PREFACE

The submillimetre wavelength range has been aptly called the last frontier in observational astronomy. During the 1960s and 1970s radioastronomers were purposefully extending their ability to observe to higher and higher frequencies, while infrared astronomers were pushing to longer and longer wavelengths with equal diligence. The interval between them was whittled down to the submillimetre range, roughly between 1 mm and 100 μm wavelength, which posed special problems of technique, difficulty of observation and astrophysical interest.

Infrared observers have traditionally used photoconductors or bolometers to detect faint infrared sources. Cooled to liquid helium temperatures, these devices are used either broad-banded, or with optical style spectrometers. Spectrophotometry performed this way is best suited to observing the dust component of the interstellar medium, although atomic and ionic studies of importance have been achieved particularly in the near infrared. Radio techniques, on the other hand, are characteristically those of superheterodyne detection, most effective over the narrowest spectral bands. These are used to best effect in observing individual spectral lines, and hence as probes of the interstellar gas. In the submillimetre range these techniques overlap, giving the range a potentially key role in the analysis of the relatively cool interstellar clouds where stars are forming. It has been all the more frustrating that the water vapour rotational band in the earth's atmosphere cuts out a great proportion of the incoming radiation between 100 μm and 1000 μm, so that observations have been made through a series of rather murky windows scattered within the range.

Several developments have now come together to produce an explosion of submillimetre possibility. New telescopes at high altitude, especially those on Mauna Kea, Hawaii, at last offer sites where eighty per cent of the ground-level water vapour path is below the observer. Balloons and aircraft give the submillimetre observer as free a run, albeit for restricted periods of time, as the ground-based observer in the visible or the radio regions. Within a few months, the IRAS satellite should be providing the first unbiased survey of point sources at the short wavelength (100 μm) end of the range. Within a few years large ground-based telescopes (30 m Franco-German, 15 m British-Dutch, 10 m U.S.) will allow observations at 1 mm wavelength with angular resolution better than that now confined to the 100 μm range.

The astrophysicists who attended the Submillimetre Wave Astronomy Conference held at Queen Mary College, London, in September 1981 (with support from the Royal Society, and under the auspices of the Royal Astronomical Society) reflected the position of the subject at the nexus of discipline and technique. There were infrared and radioastronomers with an admixture of theoretical chemists specializing in astrophysical problems. While the subject is moving away from the phase where advances in technique dominate astrophysical results, specialists in the newest techniques formed an important contingent.

A key topic current in submillimetre astronomy is the analysis of giant molecular clouds on a galaxy-wide scale. The first section of the book reflects this strong interest, and shows where major advances are being made. Using the CO molecule as the prime tracer ,clouds of molecular hydrogen at temperatures below 50 K, sheltered from direct starlight by their internal dust, can be mapped throughout the galaxy. As CO allows radial velocity to be measured directly, the classical methods developed by Oort enable these cloud complexes to be positioned within the galaxy. We know that these clouds form the matrix out of which new star clusters form. We also know that their lifetimes are short, that they dissociate within 10^7 years or so, and that new clouds must form in order to replenish the stock from which the spiral arms themselves can continually regenerate. An attack on all of these phases is now being mounted by observers and theorists. Improvements in our understanding of the formation of the clouds themselves, how they are distributed in the galactic plane, and how the conditions within them become ripe for star formation are all represented here.

In the second section we are looking with spectroscopic methods at individual clouds and cloud groups. Some of these, the Orion and the M17 clouds for example, are favourites with observers, since they contain many different molecular species, are large, bright and therefore relatively easy to observe. In this section the coming together of infrared and radio techniques is seen at its most striking with the former reaching up to 120 μm wavelength as observed from aircraft, and the latter down to 430 μm as seen from the ground. Here also we see work on the outer atmospheres of expanding stars, and detections of external galaxies. These two submillimetre fields are at their inception, and will undoubtedly increase rapidly in importance in the near future, as the big telescopes bring improved angular resolution.

Section three describes molecule formation, and shows the increasingly fruitful collaboration between those coming from backgrounds in chemistry and in astrophysics. Laboratory spectroscopists have been able to point the direction to observers by predicting frequencies and intensities of new species, and observers have responded by detecting tens of molecules and radicals, together with their isotopically substituted variants. An important programme is to relate the observed abundances of these species in the interstellar medium to those predicted from theoretical models for the formation of their constituent elements. The intervening chemical processes (reactions in the gase phase or on the surfaces of dust grains) make it difficult to relate these observations directly to stellar evolution theory or, for deuterium and helium to conditions within the primaeval cosmic fireball, but the prizes in improving our fundamental understanding in these two areas are great.

We round off the volume with a short section on instrumentation which picks out salient development points. Most important here is the fostering of new techniques in high frequency radioastronomy. New local oscillators, based on principles related to that of the maser, new cryogenic mixers based on the Josephson and related quartum effects, and new spectrometers ("backends") based on acousto-optic techniques are in the course of development. When used on the new large telescopes these will enable the next generation of observers to extend to external galaxies the kinds of studies represented, for our own galaxy, in this book.

Queen Mary College has been an active centre for submillimetre astronomical research since the 1960s when the subject began. It was an appropriate venue for the conference, and provided an agreeable setting for the presentation of a lively picture of an exciting field of research.

March/April 1982

CONTENTS

SECTION I

Large-scale structure and radiative transfer within interstellar clouds

THE FORMATION OF GIANT CLOUD COMPLEXES

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Abstract. Various formation mechanisms for giant cloud complexes are reviewed. We show as an example how the giant molecular clouds and OB associations in the Orion, Perseus and Sco-Cen regions could have formed as condensations in Lindblad's expanding ring. A new model for the ring is proposed which includes these features in addition to several other prominent cloud complexes in the solar neighborhood. We also discuss the formation of star complexes and the triggering of cloud formation by spiral density waves. A distinction between primary and secondary cloud formation mechanisms is emphasized.

Giant molecular clouds form by a combination of processes that operate on very large scales in the interstellar medium. These clouds are associated with known spiral arm tracers, namely the OB associations (Lada *et al*. 1979), and they appear to highlight the spiral arm structure better than H I (Cohen *et al*. 1980). To the extent that the *ratio* of molecular to atomic hydrogen *increases* in the spiral arms over that in the interarm regions (Cohen *et al*. 1980), molecular clouds must *form* in the arms, and most of them must get destroyed before they reach the next arm. A theory of cloud formation must explain how a spiral arm can trigger their growth, and how the clouds evolve once they form.

There are two basic categories for the various mechanisms of cloud formation: *primary* mechanisms form first-generation clouds out of a quiescent interstellar medium, and *secondary* mechanisms form later-generation clouds after stimulation from processes associated with the first generation of clouds. These two mechanisms probably operate simultaneously in all spiral galaxies, including our own, although the relative importance of each mechanism may vary from galaxy to galaxy, or with the phase of a spiral wave in any one galaxy. As an example, consider a first generation of stars whose H II regions, winds and supernovae exert a pressure on the cloud that formed it, and on the surrounding interstellar medium. Such pressures can disrupt a primary cloud and move it aside, and they can sweep up a large shell or ring in the interstellar medium. Secondary cloud formation occurs when the first generation cloud recollapses, or when the swept-up shell collapses. Observations indicate that the distances between primary and secondary generations of star formation can be 100 to 300 pc or more, and the time intervals between generations can be 20 to 100 million years.

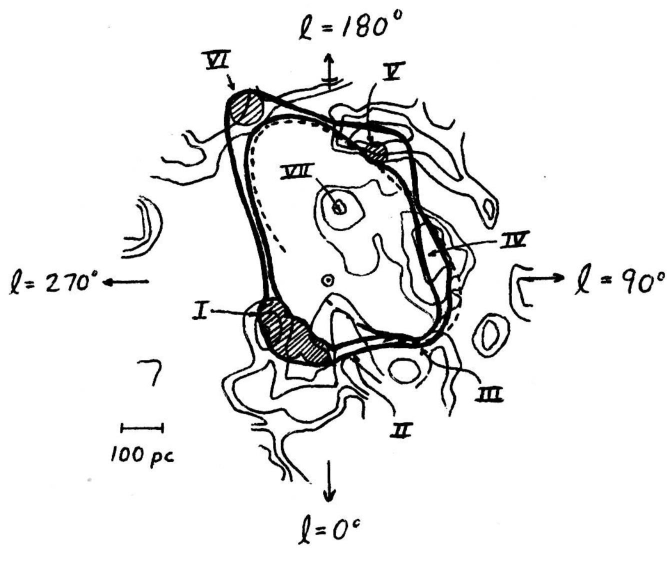
Evidence for secondary cloud formation is all around us. One of the best examples occurs in giant star complexes (Efremov 1979). A star complex is a composite of several adjacent and nearly contemporary star clusters, as defined by their common halo of red supergiants and Cepheid variables. Star complexes extend for several hundred parsecs along the galactic plane, and they include stars with an age span of up to 50 or 100 million years. A good example of a star complex is the aggregate of young clusters and dense molecular clouds within 200 to 300 pc of the double star cluster h and χ Persei. The youngest clusters in this region are IC 1805, IC 1848, and IC 1795 (which are also the giant radio sources W5, W4, and W3, respectively). The older stars in h and χ Persei formed about 20 million years ago (Schild 1967), IC 1848 and IC 1805 began forming stars about 5 million years ago (Stothers 1972), and IC 1795 was provoked into forming stars less than 1 million years ago, by the expansion of the H II region around IC 1805 (Lada et al. 1978). The entire complex shows indirect evidence for (1) a first generation of dense clouds that must have been present in the past to produce h and χ Persei, (2) the subsequent removal of these clouds from the vicinity of h and χ Persei, and (3) a second generation of dense clouds now observed to be forming IC 1848, IC 1805, and IC 1795. The clustering of these star formation sites is probably not coincidental: Efremov (1979) catalogued about 35 such regions.

The sequential star formation process (Elmegreen & Lada 1977) that formed IC 1795 differs from the mechanism of cloud regeneration discussed here: sequential star formation occurs in single clouds over small regions (1 to 50 pc) and in short time intervals (1 to 10 million years); i.e., it occurs during the disruption of a single cloud. In contrast, cloud regeneration occurs over a much larger region and in a longer time interval after the previously disrupted cloud and any associated shells of matter recollapse into new clouds.

More direct and spectacular evidence for cloud regeneration on a large scale comes from H I and CO observations of the solar neighborhood. The sun appears to be surrounded by a large, expanding ring of gas and dust that was discovered first as a source of H I emission by Lindblad (1967), and later as a source of CO emission by Cohen et al. (1980). Dame and Thaddeus recently mapped the nearby side of this ring (as reported by Professor Thaddeus at this conference), and they found that it coincides with the Great Dark Rift in the Ophiuchus-to-Cygnus region of the Milky Way. The Great Rift is therefore a molecular and atomic cloud, with a physical size similar to that of other giant molecular clouds (100 pc), and an age too young or density too low to be forming stars at the present time. The Great Rift appears to have been swept up by the same pressures that formed the Lindblad ring.

The Lindblad ring may be responsible for forming more than the Great Rift, however. The OB associations in Orion (Ori OB 1), Perseus (Per OB 2), and the Oph-Sco-Cen region are located near the periphery of the Lindblad ring, and the average radial velocities of the Orion and Perseus molecular clouds are similar to the expansion velocities of the Lindblad ring at the same positions. Figure 1 shows the distribution of all the prominent clouds in the solar neighborhood, with the cloud sizes drawn approximately to scale. The perspective is that of an observer outside the galactic plane. To make this figure, we have included: (1) light solid lines: the large-scale distribution of dust within $\pm$ 50 pc of the plane, plotted as contours of equal gas density with contour values of 1.2 cm^{-3}, 2.5 cm^{-3}, 5 cm^{-3}, and 10 cm^{-3} (from Lucke 1978, Figure 8, with a conversion of dust to gas from Jenkins and Savage 1974). (2) Cross-hatched circles: all of the OB associations within 500 pc of the sun are drawn with circle sizes equal to their largest projected diameters (from Blaauw 1964). (3) Light dashed ellipse: a simple model for the Lindblad ring (from Lindblad et al. 1973). (4) Heavy oval: the model for the Lindblad ring proposed here. (5) Circle-dot: the position of the sun. Various features that we believe to be associated with the Lindblad ring are labeled with Roman numerals and listed in Table 1.

Figure 1: Various components of the interstellar medium near the solar neighborhood are superposed. The light contours outline dust clouds (Lucke 1978), the cross-hatched circles are OB associations (Blaauw 1964), the dashed ellipse is the model for an expanding H I ring proposed by Lindblad et al. (1973), and the two heavy lines represent the model for the ring proposed here. The features indicated by Roman numerals are described in Table 1.



The origin of the Lindblad ring is unknown, but its expansion age is around 6×10^7 yrs (Lindblad et al. 1973). The ring expands so slowly (i.e., 4 km s^{-1} plus a component from galactic differential rotation) that the stars or star cluster originally responsible for the energy input to the ring could have already moved far outside of the ring. At a modest velocity of 10 km s^{-1}, the pressurizing cluster could now be more than 2 ring radii away from the ring's center. In order to make such a ring, the hypothetical cluster would have to deposit a large amount of energy ($\gtrsim10^{51}$ ergs) into the interstellar medium in a time short ($\lesssim10^7$ yrs) compared to the cluster crossing time over a ring radius; the corresponding kinematic power input would have been 10^{51} ergs/10^7 yrs$\geq10^3$ $L_\odot$. Perhaps a burst of OB star formation in a cluster that was once located in the center of the ring delivered the required kinetic energy to the local interstellar gas.

Let us examine Figure 1 and Table 1 closely. The model for the Lindblad ring proposed here is very similar to

TABLE 1: Prominent Young Features Associated with Lindblad's Ring

Region	ℓ	D	Description
Ring Components:			
I	289.6	155	IC2602
	292-312	160	Lower Centaurus-Crux OB association
	312-341	170	Upper Centaurus-Lupus OB association
	341-2	170	Upper Centaurus-Sco OB2 association
II	390-15	120-200	Ophiuchus molecular cloud and a large dust cloud
III	0-50	100-250	Great Dark Rift in Milky Way
IV	90-120	200-300	Large dust cloud
V	150-170	320-420	Per OB2 association, giant molecular cloud, and a large dust cloud
VI	199-210	460	Ori OB1 association, giant molecular cloud, and a dust cloud
Ring Interior:			
VII	150-185	110-220	Taurus molecular clouds and a small dust complex