Aust. J. Phys., 1994, **47**, 577–84

John Bolton as a Pioneer of OH Spectroscopy*

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Abstract

Following the discovery of interstellar OH by US astronomers in 1963, John Bolton and colleagues used the Parkes telescope for pioneering work on the OH clouds towards the centre of our galaxy. The OH was found to have a large range of velocities. All four ground-state transitions at 1·6 GHz were detected, but with relative intensities differing markedly from theoretical and laboratory values.

Most people remember John Bolton for his work on the continuum emission of discrete radio sources, the pioneering optical identifications in the late 1940s, and the cataloguing, positioning and identification work he later carried out at Parkes. However, John was a person of considerable versatility who also played a significant role in the first observations of the hydroxyl radical (OH) in interstellar molecular clouds. This was the first interstellar molecule detected at radio frequencies, and the observations marked the beginning of a field of research which now dominates millimetre-wavelength radio astronomy.

In the early 1950s, neutral atomic hydrogen (HI) clouds were the only detectable 'cosmic radio stations', emitting narrowband signals due to a 'spin-flip' of the electrons in the HI atoms. However, radio astronomers suspected that signals associated with some molecules should also be detectable. One of these molecules was the hydroxyl molecule (OH). It has energy states (Fig. 1) split by 'lambda doubling', due to interaction between the rotation of the nuclei and an unpaired electron in its orbit. Hyperfine interaction with the unpaired spin of the proton further splits the levels. Thus, for a particular energy state, there are four hyperfine levels, giving rise to four transitions.

In 1956, US astronomers A. H. Barrett and A. E. Lilley knew the approximate frequencies of the 1·6-GHz ground-state ($^2\Pi_{3/2}$, $J = \frac{3}{2}$) transitions of OH, and searched for the strongest transition in absorption against the strong radio source Cassiopeia A (Barrett and Lilley 1957). Significant narrowband HI absorption had previously been detected in this direction. However, the search failed because the OH frequencies were not known accurately enough.

In 1959, using laboratory measurements, C. H. Townes' group at Columbia University established the frequencies for the two strongest OH transitions as 1665·46±0·03 and 1667·34±0·03 MHz (Ehrenstein *et al.* 1959). Surprisingly, no

* Refereed paper based on a contribution to the John G. Bolton Memorial Symposium held at the Parkes Observatory, 9–10 December 1993.

0004-9506/94/050577$05.00

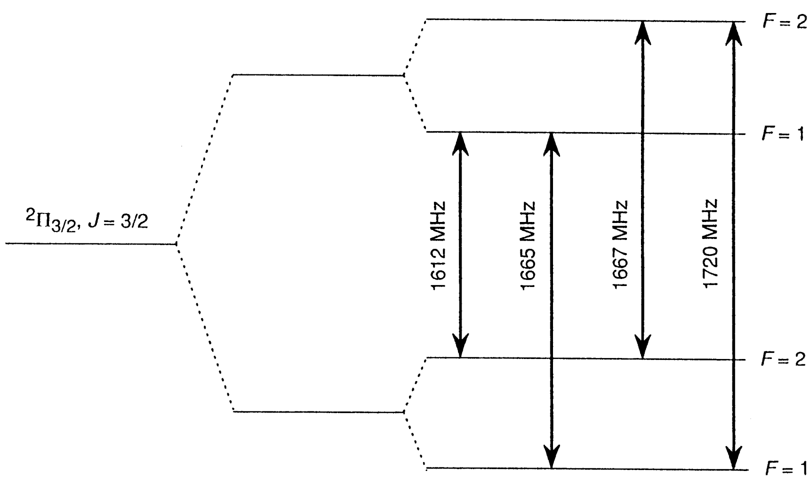

Fig. 1. The energy levels of the $^2\Pi_{3/2}$, $J = \frac{3}{2}$ ground state of OH, showing the four transitions. In the laboratory, the transition intensities are in the ratio (1612 : 1665 : 1667 : 1720) 1 : 5 : 9 : 1.

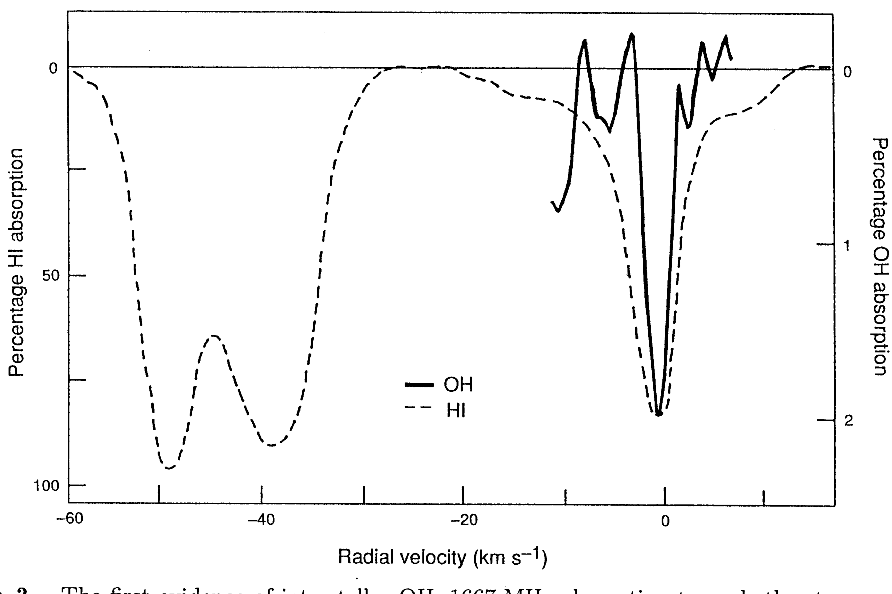

Fig. 2. The first evidence of interstellar OH: 1667-MHz absorption towards the strong radio source Cassiopeia A. For comparison, the corresponding HI absorption is also shown.

serious attempt was made to use this new information until 1963, when S. Weinreb, A. H. Barrett, M. L. Meeks and J. C. Henry finally detected OH absorption towards Cassiopeia A (Weinreb *et al.* 1963; Fig. 2). From a comparison with the HI absorption lines originating in the same molecular clouds, more accurate OH frequencies (1665·402 and 1667·357 MHz) were derived; these were within 1–2 kHz of the values that we use today.

Word of the discovery spread rapidly. In Australia, the Parkes radio telescope was in its first years of operation, and performing quite nicely. John Bolton, in association with Karel van Damme, Brian Robinson, and Frank ('FF') Gardner, rapidly improvised a receiving system to confirm the discovery. Cassiopeia A is a northern radio source which cannot be seen from the Southern Hemisphere, and so another strong radio source associated with strong HI absorption, Sagittarius A, was chosen. That this source was coincident with the centre of our Galaxy was immaterial at the time. The HI absorption spectrum has several features; the strongest by far occurs at a radial velocity (with respect to the local standard of rest) near $0\,\mathrm{km\,s^{-1}}$. About a month after the initial OH detection, observations made at Parkes over a velocity range of $60\,\mathrm{km\,s^{-1}}$ centred on the laboratory frequencies, revealed 1665- and 1667-MHz OH absorption near zero velocity (Bolton *et al.* 1964*b*). So great was the interest that, within three weeks, OH had been detected by two other American groups.

The *Nature* article announcing the Australian detection failed to mention that the absorption features for both transitions were superimposed on steeply sloping baselines. Initially, the sloping baselines were thought to be caused by the receiving equipment but, on investigation, this was discounted. Follow-up observations of OH over a wider velocity range produced several surprises (Robinson *et al.* 1964). The sloping baseline turned out to be a wide absorption line centred near $40\,\mathrm{km\,s^{-1}}$, and much stronger than the zero-velocity feature. Although it coincided with an HI feature, the latter was much weaker. Unexpectedly, the ratio of the intensities at 1665 and 1667 MHz was 5 : 6, rather than the laboratory ratio of 5 : 9. OH counterparts to HI features near –30 and $-50\,\mathrm{km\,s^{-1}}$ were also detected, but were much weaker.

In 1964, laboratory measurements by H. E. Radford (Radford 1964) provided accurate frequencies of 1612·231 and 1720·529 MHz for the two weaker OH transitions. Further observations from Parkes towards Sagittarius A, by Frank Gardner, Brian Robinson, John Bolton and Karel van Damme (Gardner *et al.* 1964), yielded prominent absorption for both transitions. In reporting the 1612-MHz results, these scientists noted without comment that the profile shape didn't quite match that at 1667 MHz. However, they were puzzled that the absorption-line ratios for the four transitions were 1 : 2·2 : 2·7 : 1, in contrast to the expected values 1 : 5 : 9 : 1 determined both theoretically and in the laboratory. They explained the results in terms of high optical depths in the range 2·7–3·5. At the same time they commented that 'an alternative explanation, such as perturbations of the populations of the levels, cannot be excluded'.

This detection story is not quite complete. Overseas, a group using the Harvard Observatory 60-ft antenna, with a beamwidth of almost 1° at the OH frequencies (about four times that of the Parkes antenna), carried out an OH study towards Sagittarius A, and detected an additional strong, wide absorption feature centred at a velocity near $-130\,\mathrm{km\,s^{-1}}$ (Goldstein *et al.* 1964). Such negative velocities had not been covered at Parkes where, because a single-channel receiver was being used, it was a lengthy procedure to construct an OH profile from a sequence of observations in which the receiver frequency tuning was stepped progressively across the required velocity range.

Back in Australia, Dick McGee joined the Parkes OH group, contributing a 48-channel spectral-line system that he and John Murray had developed for observations of Galactic HI. Subsequent, more extensive OH observations (Bolton *et al.* 1964*a*) showed that the total extent of the absorption covered velocities from -230 to $+100\,\mathrm{km\,s^{-1}}$ (Fig. 3). In addition, OH absorption was detected along the Galactic equator at all longitudes within 2° of the Galactic centre.

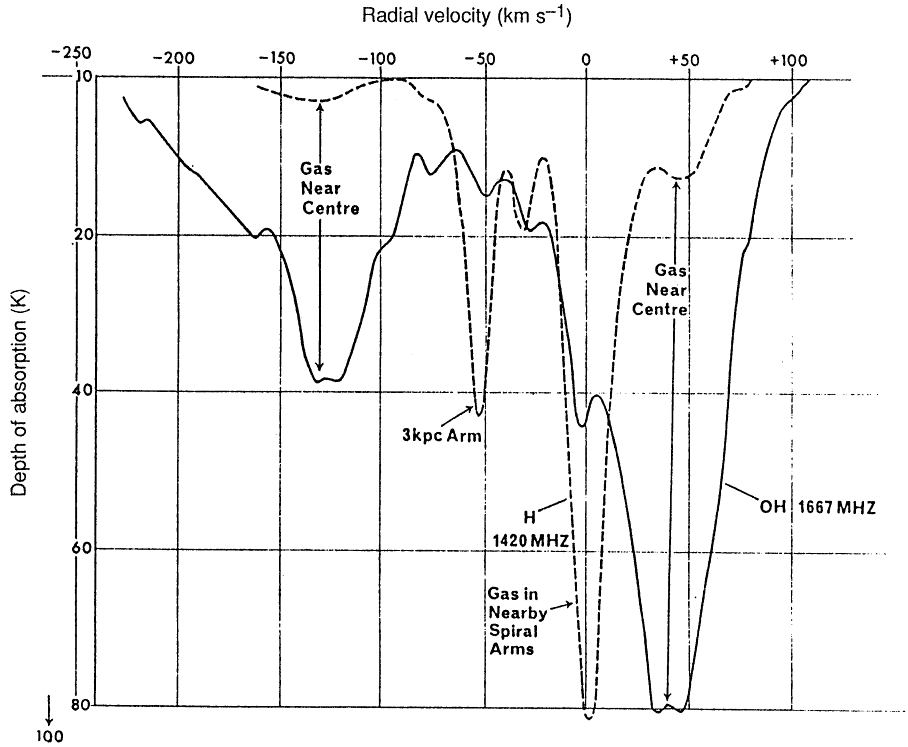

Fig. 3. The total 1667-MHz OH absorption-line profile towards Sagittarius A, shown together with the corresponding HI profile. The profiles show features at similar velocities but differing greatly in intensity.

For the first time it was possible to distinguish individual OH clouds extended in longitude.

Bolton collaborated in only one more OH project at Parkes. This project used observations towards other directions to show that the anomalous intensity ratios for the four transitions must be due to disturbed populations of the energy levels involved, rather than to high optical depths (McGee *et al.* 1965). The observed positions included several thermal continuum (HII) regions towards which H. C. Weaver and colleagues, using the Hat Creek 85-ft antenna, had discovered intense narrowband emission near 1665 and 1667 MHz (Weaver *et al.* 1965). The Americans attributed this emission to an 'unidentified microwave line' (which they locally labelled Mysterium), but the Parkes team decided that the frequency coincidence was too great, and that the emission lines were OH transitions. This conclusion was correct; the Americans had stumbled upon the first OH maser emission.

That was about the end of the John Bolton OH story. He went off to concentrate on his extragalactic radio source work. However, as a legacy to John, the OH research at Parkes continued. Brian Robinson and Dick McGee rounded off the Galactic centre survey work, which is best summarised by McGee (1970) and Robinson and McGee (1970). Subsequent projects included the

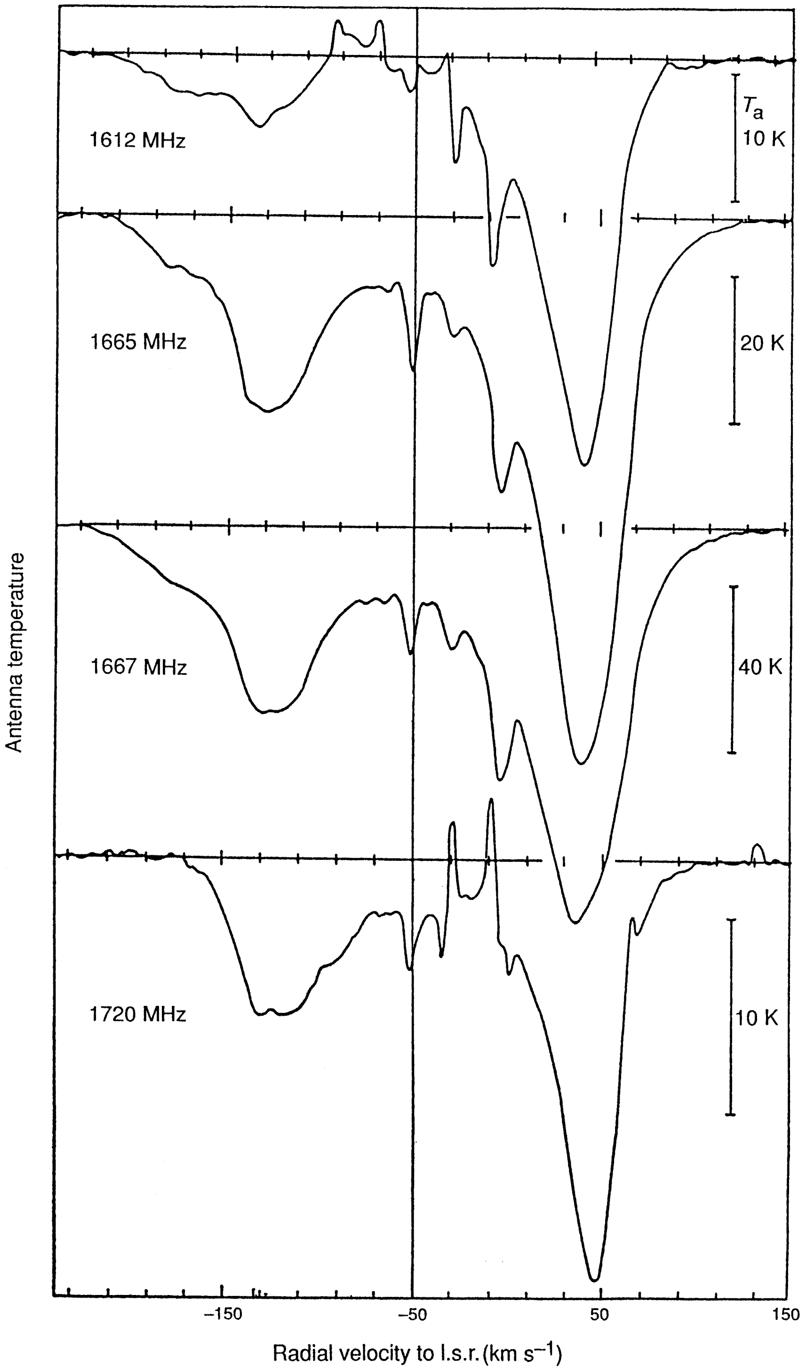

Fig. 4. Line profiles for the four OH ground-state transitions observed towards Sagittarius A. Note the paired anomalous behaviour of the 1612- and 1720-MHz transitions.

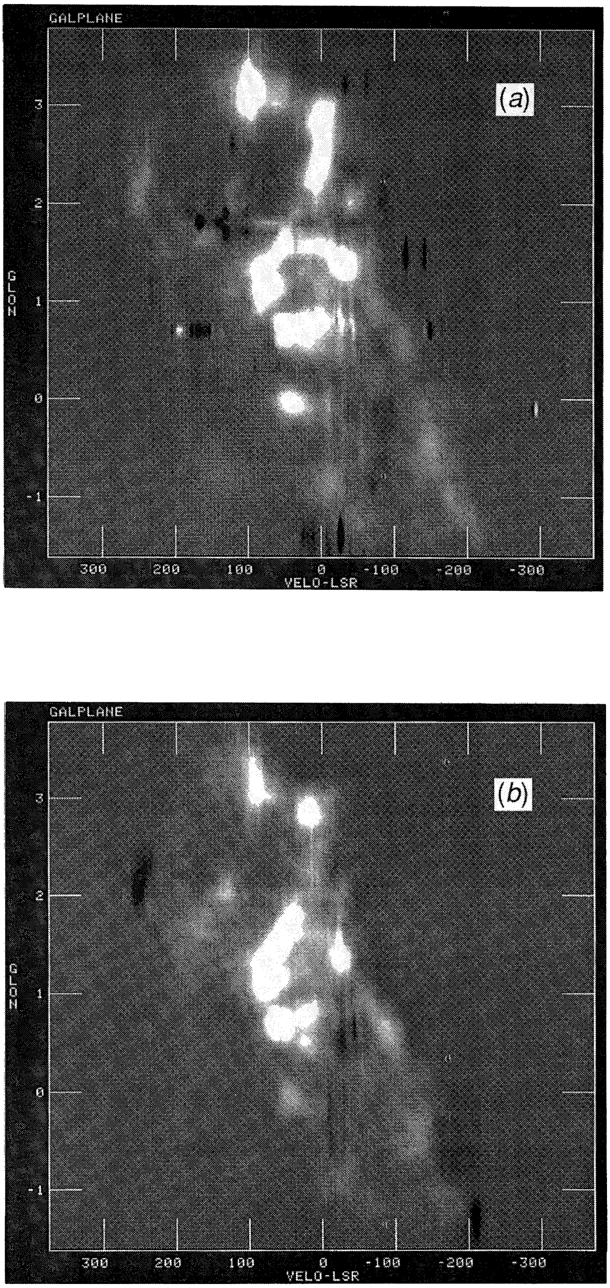

Fig. 5. Unfinished Parkes OH study: the velocity–longitude distribution of (*a*) 1612- and (*b*) 1720-MHz OH in the Galactic centre region. The grey scale refers to line-to-continuum ratios; these are more directly related to OH line-of-sight densities than OH absorption intensities.

surveying of OH along the Galactic plane, observations of OH isotopic and higher state transitions, polarisation and time variability studies of maser emission, detection of extragalactic OH, etc. Other observatories around the world were also active—observations at Jodrell Bank (e.g. Cohen 1982) resulted in one of the best surveys of OH in the Galactic centre region.

During the 1970s, Frank Gardner and I became interested in OH towards the central regions of our Galaxy. We believed, contrary to conclusions reached by our Australian predecessors, that OH distributions showed the same extended cloud patterns seen for other molecules (e.g. Whiteoak and Gardner 1979) and HI, although the relative intensities of features could differ. This is obvious in the OH absorption towards Sagittarius A (Fig. 4): the $-130\ \mathrm{km\,s^{-1}}$ absorption from the molecular ring; the $-55\ \mathrm{km\,s^{-1}}$ absorption from the '3-kpc spiral arm' of HI fame; $-30\ \mathrm{km\,s^{-1}}$ absorption from a similar spiral feature; zero-velocity absorption mostly from clouds closest to us; and $40\ \mathrm{km\,s^{-1}}$ absorption from a cloud near Sagittarius A. The innermost cloud appears to be moving contrary to the general outwards movement suggested by the other clouds. However, studies during the last ten years have shown that this cloud is located beyond the nucleus of our Galaxy, and is therefore also moving outwards from the nucleus.

The results for the four ground-state transitions towards Sagittarius A and other positions were somewhat unexpected (Whiteoak and Gardner 1976). Not only were the 1612-MHz/1720-MHz paired anomalies present in some clouds, but also the anomalous behaviour reversed from one position to another in a cloud, and even across the velocity spread observed in a cloud. These results suggested that the anomalous behaviour was more likely to be related to excitation effects arising close to the clouds than to some central cause such as infrared radiation associated with the Galactic nucleus.

To pursue the question further, we carried out a full survey of the Galactic centre region for all four transitions. The preliminary results (Fig. 5) confirmed the earlier conclusions. We suspected that the results would be related to the distribution of infrared radiation, but this was before the era of IRAS surveys etc. Before we could complete the study, Frank drifted off into retirement, I sold my soul to the Australia Telescope project, and the data remain virtually untouched on a slowly disintegrating computer tape. Maybe some day someone will revive the issue and complete the studies, which John Bolton helped to pioneer so many years earlier.

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Manuscript received 3 February, accepted 1 July 1994