The Galactic Cosmic-Ray Ionization Rate implied by observations of atomic and molecular ions

> David Neufeld Johns Hopkins University

Collaborators: Mark Wolfire, Nick Indriolo, Maryvonne Gerin, Javier Goicoechea, Paule Sonnentrucker, Michael Kaufman, David Hollenbach, Raymond Oonk, Xander Tielens

Funding: Herschel Project, NASA ADAP program

Outline

- Cosmic-rays: Introduction
- The CR ionization rate in diffuse molecular clouds, as determined from observations of H₃⁺
- The CR ionization rate in diffuse *atomic* clouds, as determined from observations of OH⁺, H₂O⁺ and ArH⁺
- Additional estimates from radio recombination lines
- Summary and conclusions

Introduction: Discovery of cosmic rays by Victor Hess



Victor F. Hess, center, departing from Vienna about 1911, was awarded the Nobel Prize in Physics in 1936. (New York Times, August 7, 2012, page D4)

Introduction: Their nature was controversial

"All the Ne Fit to P	ws That's rint."	The N	lew Y	ork d	Irmes	LATE CIT	Y EDITION
VOL. LXXXIINo. 27	370. Baiered as I	berned-Jings Matter, Dem Tech, S. Y.	Copyright, 1992, by The I NEW YORK, SATUEDA	Y. DECEMBER 31, 1932.	****+ T	WO CENTS In First Million	CENTS FOCE CENTS Electron Each
MILLIVAN DETODTS	India Opens Health Institute	POOSEVELT WORKS	Mussolini Will Curb	Industrial Output	O'DDIEN TO EVTEND	1932 Passenger Auto Plates	I FUMAN TAKES OAT
MILLINAN RETURIS	Given by Rockefeller Interests	MADEL HOUGE CONDOC	As a Means of	Combating Depression	DECODM DDACD AM.	Become Useless at Midnight	DDIVATELY TONICU
HUILYTUCUMPTUN	CALCUTTA, Dec. 30 In the abrence of the Vicercy, who is	WITH HOUSE CHIEFS	He Yin Am	uchained Press.	REFURM PRUGRAM;	Registration plates for passen- ger automobiles expire at mid- night tonight, after which time	PRIVATELY TUNIGH
EN COSMIC RAY CLASH	slightly indisposed, Sir John An- densen, the Governor of Bengal, exceed today the Ali-India Insti-	FOR FEDERAL CUTS	ROME. Dis. 30 The regula- tion of industry, with the earling of "studential branches of balances	require its lively and expendive spirit in new markets as soon as	TAKES OATH TODAY	it will be illegal to drive a car in this State not equipped with a	IN CEREMONY HER
Dabata of Blast' Theorists	tute of Hygiene and Public Health, made possible by the gift	Barrente at Washinston In	without which the crisis cannot be overcome." Is being proparat by	utilizing that inventive spirit which is our greatest wealth. But those		reau of Motor Vehicles where the plates may be obtained will	Black Channel by Death
Brings Drama to Session	of the building and equipment. India furnishes the staff and	Close Contact With Him	cial esemission of his Ministry of Corporations.	irregular industrial expansions that ware distated rather by bankers' than manufacturers' standards can	Only Marks Beginning of	be open until soon today. They will be closed tensorvow and Mon- day.	His Sister-Brother Will
of Nation's Scientists.	provides for maintenance of the institute, which is in a effore, the completion of the licheol of Tropi-	on Budget.	The Pressler says "this provision is necessary to facilitate the process of gradually analian down," instand	not be permitted, for there have been too many dolerous experiences for the Fracial State to reference	Survey, He Says.	Figuras given out at the bu- reau yesterday showed a drop of	Swear Him Into Office.
THEIR DATA AT VARIANCE	cal Medicine adjoining. By research and teaching it will bridge the guif between knowl-	NEW SLASH PLEASES HIM	of speeding up, production. The commission is working on details of laws which will be effective in	any more." To reduce unemployment during	HE WILL DEFER OUSTERS	licenses recorded up to the close of business Thursday, when 245,- 506 sets had been issued, as com-	ALBANY PROGRAM STAN
New Findings of His Ex-Pupil	enne in India. Lieut. Col. A. D. Stewart, for-	Collins of Appropriations Body	Under a statute aircody adopted no plant in whatever line of manu-	to oust \$130,000,000 was started by Ealy sarty this month. About half	To Put Off 'House-Cleaning'	pared with 275,966 on the same day last year. The bureau's headquarters at	Inaugural Not Affected
Lead to Thrust by Millikan	ferly Professor of Hygiene at the School of Tropical Medicine. is director of the institute.	Visits Albany-Sales Tax Is Due for Defeat on Vote	facture may be built or calorged without the government's occurnit. This law was presented to the	of the money will be spent by Spring, and 'he povernment em- pects the work to keep 200,000 men	Until Plan to Reorganize	Centre and Worth Streets yester- day was througed all day will ap-	Governor-Elect Cancels H Social Engagements.
	DEVELOV TO COEED		Chamber by the Preaser himself in his capacity of Minister of Corpora-	at work, thus aducing the n.m.		about 15,500 plates ware invoid during the day at the fifteen main	
PROF. RUSSELL ELECTED	REVERKE IN PRED	MRS. MOONEY IS HEARD	"It is well fenows," the Premier explained when he advocated the	The plan calls for the erection of bridges, public buildings and sque-	SENATOR HOFSTADTER OUT	and branch offices in the five bor- sughs of the city.	ROOSEVELT LUNCHEON O
Astronomer Heads Association-	OLD YEAR, HAIL NEW	Rossevelt Sending Her Plas for	measure, "that although a crisis halts new initiative and invest- ments, nevertheless in the midel of	costs and the construction of roads. The work is distributed over all parts of the country.	Resigns as Inquiry Chairman in	HOOVER HITS LUCK	President-shell and His Wife
Secret of Purple Gold in Tomb of Tut-ankh-Aman Radissovered.		Son to California-Dinner Tanight His Last as State Executive,	the depression there is always some industry which does not voluntarily	Under Premier Monsulat's order all Fascist clubs opened synghett bilighang for the moder but Wirder	Three-Line Letter to Fearon- Goes an Banch Tuesday,	CETC 7 FOOT FIGH	Attend Ball Smith to Spea at State Exercises Nonday.
By WILLIAM L. LAURENCE.	Celebration Along Breadway Tonight to Be as Hearty	By JAMES A. HAGERTY.	erisia. "Statian industry must certainly	and these are to be continued throughout this suid season.	Restort W. Modelafter resigned	GE121-LOO1 HI2H	Governor-dest Herbert H. L
Special to Two New Your Tourn. ATLANTIC CUTY, Dec. 39 Pro-	as in Beem Years.	Special to THE NEW York Thins. ALBANY, Dec. 30 Democratic	AMAZON WAR ZONE	WINTER OUTS POST	yesterday as chairman of the legis- lative investigating committee	He Also Bags 2 Other 'Sailers'	man arrived in New York last ni from Albany, and will take
the Nobel Prize in physics for being the first to measure the charge of	NO DRY RAIDS PLANNED	badders in the House of Representa- tives are acting with the knowledge and assessed of Franklin D. Resse.	AMALON WAR LONG	NINTER COTTO FOOT	which bears his name is order that he might he prepared to take his	and a Dolphin in Best	where in this site before midel
the electron, and his former pupil, Prefessor Aribur H. Compton, who won the Nebel Prize for the dis-		velt, President-elect, in cutting ap- preprintions as the first step to-	TUUCHES 4 NATIONS	IN ANTI-KUENIG KUW	on Jan. 5. Samuel Seabury, coun-	Angling of Career.	tonight. He will be sworn in his brother, Judge Irving Leks
covery of the Compton effect, pra- sented today before the American	Noise at Times Square Will Be Broadcast to Foreign Lands	Governor Received todget.	Bearil and Feundar Have an	Resigns Leadership After He	Island to spend the week-end, and for the day there was a buil in the	PRIZE FIGHTS AN HOUR	of the State Court of Appeals, w
Science two diametrically opposed hypotheses on the nature of the	-Services in Churches.	Regressedative Ross Collins of Mis- nissippi, who is a massher of the	Interest in Dispute of	and Mack Disagree on Way	activities of groups nocking to housik the power of Tammany.	Catch for the Entire Party Off	of the Governor-cost on the to occasions when he has taken off
cosmic ray, in the study of which Dr. Millikan is the American pla- near.	New York's millions will hid an	chairman of its subcommittee on appropriations for the War Depart-	Colombia and Peru.	to Reorganize Party.	On the other side of the fence, however, the activity increased, with the handling to Mayor sized	Florida Totals 14-Shark	The State administration pas- iets Mr. Lehman's hands at
In an atmosphere surcharged with drams, in which the human	and will bespeak a heartily desired prosperous New Year, according to	ment. When he left for Washing- ten, Mr. Collins had a clear idea of Governor Research's views on the	10.000 TROOPS GATHERING	CLUB INSISTS HE STAT	John P. O'Brien by his charter re-	Robs Senator Austin.	stroke of midnight tonight for those of Problemi-elset Roosev Nermally, the original logostroat
element was by no means lacking, the two protagonists presented their views with the vehemance and	their wont, with noisy street cele brattons, night club and theatre	Recently for economy. Testerday, Governor Rossevelt			reforms in the city government. Judge O'Brien, in an interview in	From a Staff Correspondent. DALM BEACH, Fin., Dec. 80	would have taken pince in Alba- but a change of pinn was made
fervor of these theoretical debates of bygone days when learned men	emit church pervices. All is all, is spits of the economic depression.	Oliver of Alabama, another mem-	Eleven Warships and 46 Planes Also Are Being Mebilized in	Meeting in an Uproar as Hi Walks Out-Resignation of	the office in the Burrigates' Court, sold he considered the report,	The bad luck that has marked President Hoover's fishing vac-	of Governor-elect Lehtgan's sist Mrs. Chars L. Limburg.
clashed over the number of angels that could dance on the point of a needle. Dr. Millikan particularly	the sily's New Tear's Eve celebra- tion promises to be an demonstra- tion as in the pure distant "hear"	tions. Today and hat night he was in conference with former Repre-	the Leticia Area.	County Chief Demanded.	ture of the present city gavara- ment, as tentative, and that it was	tion in Bouthern waters turned to- day, the President having one of	There will be no change in i formal inarguration ceremoni
sprinkled his talk with remarks di- rectly aimed at his antagonist's	years. Times Square, as trual, will be	was chairman of the Appropria- tions Committee during the World	By JOHN W. WHITE.	The Republican Club of the Fit	In no way to be considered the final work of his committee.	in all his years of angling. His party bagged eleven salifish,	at the State Capitol in Albany Monday. The official inaugurati
visce collings between the two men when they met after the	thronged by merry-making theu- nands, assembled is shout a greet ing to 1523 when the big ball of	War and is one of his advisors on the budget.	Restal Cable to TRA New York, TUNE, BUENOS ALRESS, Dec. 20 1200.0	teenth Assembly District, the lead ing unit of the party in the city started out last night to oust Sam	quility likely that the incursionia	two dolphins and an amberical, with three salified, and one of the dolphing being handed by Mr.	will be of the most severe simpli- this year, according to plans that
debate was ever. Dr. Millitza holds that the cosmic way are phytone, builds of light.	light slides down the flagstaff atop the Times Building, herald	It was learned from the Gover- nor that their discussion was on	six fighting planes are being mobilized in the Leticia region, repre-	usi 5. Evenig as insider of the party in Manhwitzer, only to find Strett, in	will be allowed to continue in their posts, if they care to, until Julge O'Brien has started the reorgani-	Heever. The prize of the lot, T feet it	Social Engagements Off.
similar in nature to the gamma- rays from radium. Such rays have	while electric lights finsh the ar- rival of the new.	finance, which was described as much breader than the budget. Pro- fessor Barmond Moley of Columbia	senting the interests of three South American republics in the dispite	half, without a club leader, and with few of the residents of the	nation suggested in the report of his committee.	President after a hard ballie that ended fifty-five minutes after the	yesterday plans for the partici-
no electric charge, travel with the speed of light, and are wave-like in rature. Professor Cogapten, on the	The encopheny of shouts, chears, bells, horns and other noise-making devices from the tesming then	University also was with the Gover- nor last night.	over pessession of a hitherto un heard-of town of 800 inhabitants	Park Avenue district who belong to the club knowing what had knought it all about.	The relignations of these commis- tioners will be on Judge O'Brien's	striks. The scars of the Prosident's sali-	all the social events that usually company the inauguration of a r Geverner. Seen after the report
other hand, holds that the examin rays are electrona, electrically	cands in Broadway will be broad- cast by radio to audiences in for-	approval in talks with friends of the way in which the House Demo-	Amanana. " General Almerido da Moura, com-	The Fifteenth is shnort unan income on two points, its opposition	desk when he walks into City Hall on Tueslay, but, according to	tan miles south of Jupiter Light and about seven miles from Palm	Mrs. Limburg's death reached beny, Governor Rossevalt
ture as the ullimate units of mailer. one of the two kinds of "bricks"	been made by the National Broad casting Company and, the Colum-	cruis are proceeding to reduce gov- ecumental expenditures. He was	manding the northern military dis trict of Bruail, left Mazaon with	to Mr. Koonig and its administration for Keyen Winter, innder of the dis triet for the last five years. But	general houserleasing that has been forecast will be held up.	Beach as the crow flies. Mr. Hoover and Lawrence Richey, his secretary, left Palm Beach at	and reception at the Executional Manalon, following the inaugh
out of which all the elements in the universe are constituted. These dia- metrically concern house here	bia Breadcasting System to station microphones in Times Square.	outs of \$40,000,000 from the hudget proposed by the Bloover administra-	for Tabatings, two solies from Leticis. Braail has two warships	the members who attrided the meeting last alght, called by Wall	Information as to Judge O'Brien's probable appointees has been com-	4:45 this morning, reaching the finhing banks about an hour later.	ceremony on Monday, had be called off.
bargely based on diametrically op- posed findings of fact.	Cataret Currew Belazed, Police Commissioner Mulrooray is Sidne to make the usual boliday	tion already had been made. The Governor was informed that Entremedative James W. Collier.	near Leticia, is sending two more and has ordered 2,000 men and also players to the frontier and one	they, to start an anti-Mesnig drive were underso that Mr. Mark and	Terristoy affirming that no single appointee has been definitely named	Mrs. Hoover and other members of the party followed in another boat, while Coast Guard cutters formed	Governor-elect would not attend dinner to be given by Governor
New Star Theory Presented. Another highlight of the associa-	concession to night clubs and caha- rots, allowing them to remain open	chairman of the Ways and Means Committee, had revived the sales	cruiser and three destroyers to Pars, at the mouth of the Amazon	Mr. Winter had disagreed over the method of precedure.	yet. There are a large number of important places now empty, in ad- dition to the new men who will	in fine directly astern of Capials Herman Gray's Sahing sloop Orea,	Mrs. Receivant at the Except Mannion in Albany tonight to members of the Gerszner's Cable
tion's sension was the presentation tonight of a new theory, based on the discovery of the armicent of	the curfew hour of 2. If the Weather Bureau forecast	killed by the Governor's opposition, and had said that he would give	nounce that these protoutions are due solely to Brazil's determination	The result was that the following chain of guests took place in 1987	eurerunds some of James J. Walk- er's commissioners, but no hint as	Richay. Fifteen minutes after reaching	The inaugural ball which will hold tonight in Albany also will
how the stars keep on creating their own fuel, by Professor Henry	proves to be correct the city will be backy enough to have clear, if conter, weather this eventue. The	upon it Wednesday, Governor Roomvell smiled, but refrained	to protect its neutrality. Branit however, is directly interested in Perso's attempt to persuide Others	succession: Mr. Rossig was denounced, while	officeholders has been given, Mr. O'Brien will take the oath	the fishing waters the President got his first satifies strike.	eccupying his bez. Governor Rosvell, and Mrs. Roosevell, hower
was elected president of the as- sociation. He succeeded Professor	forecaster said last night that it would rain most of today, but that	from comment. It is believed here that the Gover-	bia to reconsider the Salomon- Lozano treaty, because Brazi	A resolution was read calling for	of office at a simple ceremony to- day in his office in the Hall of Records after be made his restrict	When the white fing that signals	will go and remain for about hour. They will not return to Ensuration Nanaton after their
John J. Abd of Johns Mopkins. Prefessor Russell presented his theory during the first Mathel Inc.	evening. The prediction also was for increasing south and southeast	ner has he expectation of the pas- negs of any general manufacturers' makes tax at this session and would	the treaty when it was signed by Paru and Colombia and is expected	his resignation and appainting Mr. Winter chairman of a committee to take up reorganization of the	nation as Decrogate to the office of the Governor at Altany. The	on the Occa the President did not pause for a rest as most finhermen	to their home at Hyde Park.
ture. Earlier in the play, Profos- sor R. W. Wood, nated physicist	winds. Andrew McCampbell, Prohibition Administrator, was intlined to be	not hesitate to become more setive in his opposition if it should appear that it had a chance to pass.	to renew territorial claims if the treaty is broken or revised. Para has 2.00 troops near Le	Republican party in Manhattan. Mr. Winter arose, spoke in favor	to be marked by simplicity, will take place at City Hall on Tounday.	proceptly halted his line and sent alaft the hits that holds the line	ably will not take possession of mannion until Monfay afterne
of Johns Highlits University, re- ported the rediscovery of the secret of the "puryle gold of Tut-anhh-	non-committal when he was asked if he were planning any entra New	Interview With Mrs. Macusy. Governor Rossevell today naw	ticis, of which 1.000, with ter planes, are at Iquites. Feru has	be done by some younger man, an	2 It is understand that Mr. O'Belen will use the report of his charter revision committee in his insura-	An hour passed before the second strike came, and this time it was	They are now domiciled in a trees suits at the Hetel Da's Clinton, Altany,
Amen," found several years ago in King Tult-ankh-Amen's tomb.	Wear's Eve work in line of duty. Mr. McCampbell said that the en- forcement of the prohibition law	Mrs. Mary Monney, 84-year-old mather of Tem Monney, and agreed	and smaller detachments to other towns along the Putumare River.	sounced he had resigned and left the elubhouse.	ration address as a pledge of what he intends to do to simulify the	the dolphin, a shimmering eliver beauty that put up a fight lasting	Under the original inaugural prass, Governor-elect Lehman
of evidence galtered in a series of very delicate experiments conduct-	was a routine job and as long an there are United States statutes that the companying or sale	for her son to Governor James Rolph Jr. of California.	Colorobia has four warehips at Para awaiting the arrival of three	moil with lead shouts of "No, no," coming from all quarters of the	ention more economical. The pub- lication of the report, prior to its	In the meantime things were hap- pening on the Miss Salty, the sloop	to have been overn in at the El wilve Mansion in Albany in presence of the Cabinet massi-
ad by him during the last fifteen years in many parts of the world, on mountain tons, in unmanned	of initatienting beverages, at New Year or at any other time, he	In dictating a letter to Governor Rolph during the afternoon, Gov-	Putumayo. A decree of the Colom- bian President on Oct. 16, 1931.	From. Finally, when the club meeting had advanced after a stapping the	official release, may, however, prompt him to make some remarks	on which Justice Stole, Senator Austin of Vermoni, Commander	immediately alter the Cabinet of ner tonight.
balloons, in speedy airplanes, at the boltoms of lakes, on ocean-going	Continued on Page Three.	Coatinued on Page Two.	fixed the army strength at 500 effi- cers and 6,000 men. The bulk of	anti-Kosnig resolution and giving	Centioned on Page Two.	Continued on Page Two.	of Secretary of State Edward Fiyan went forward yesterday w
steamers and al regions in the far worth of Canada. In mone of his experiments, he said, had he found	Dill Proposes That Se By Observing Effe	nators Test 3.2 Beer acts on Jury of Tasters	Upper Putumayo, where the Freed- dent recently inspected thirty fight-	of the county committee from the district was called, on the spot, and	Police Radio Alarm F 4 Thugs Seized Robbi	oils Hold-Up of Club; nr 30 Men and Wamen	the work of preparing the Ass bly chamber at Alhany for the
any appreciable variation in the in- tensity of the rays.	Restal to Tax	few Ties Truce.	Field Hospitals Established.	a pessintion asking that Mr. Winter reconsider was adopted unanimous	The patient and in called		While the inauguration will be a ple, the attendance is expected
ticles of matter, he argued, they would be deflected by the earth's	WARHINGTON, Dec. 20 Senator Diff thinks the heat way to de-	Senator Dill is in favor of the pos- ange of a beer bill which does not	dressing stations in towns around Florencia, where twenty-five Bo-	wait on him today and tail him that the club wanted him to continue as	up another quick victory over gang- dom last night when crows of two	ans. About 100 members of the club.	has slready disposed of all the mission tickets to both the Ass
would result in the detection of more of these rays in areas mean	beer is intesteating is to try R on these who would drink R. So as	individual States to fix their own, and is drawing up such a measure	pold society girls already are as seabled for Red Cross duty. Co- tembra is runking medical and an	The resolution asking him to stay was proposed by Mr. Mark, and	finar clubroam of the Brucklyn Civin Club at 559 Hedford Avanua.	an organisation of young people in terested in civic affairs, had at- tended a meeting earlier in the even	ly chamber and to the Ber chamber, which is being wired in conjuged with amplifiers in a
the north and south magnetic poles. But no such variation had	will propose Monday to the Senate Judiciary Committee, of which he	aut holds that if the Judiciary Com- mittee is to define 3.2 per cent beer	gical supplies to these stations by planes and automobiles. Thus five	was seconded by Alderman Joseph Clark Baldwin 5d and Assembly	in the Williamsburg district, caught four armed men robbing	ning. Thirty of them tarvied in the chib rooms when the meeting	eration for an overflow audio The covencey will begin at a
strongest kied of proof, he rea-	taxters," consisting of average men, he choses on which a brew of 2.2	"It is time we had some prio-	of Bouth America's ten republics are practically on a war footing, as Belivia and Paragusy have been	mittee named to wait on him in choice Mr. Saidwin, Mrs. Neth	man, and captured all four without firing a shot.	or playing cards. Shortly before midnight, the four	Places for 100 Notables.
would not be affected by the mag- netic pull of the earth.	This jury, relected by the com- mittee and seated before it, would,	the subject of whether 3.2 per cent beer is intoxicating," the Senator	batting for personation of the Chaos wilderness further south since June. Another, Reventer, has come	William Warner Hoppin, former bader, and Mr. Matk.	The police were summoned by the pre-ident of the club, Dr. Murray Lewin, an honorary argues of the	men buret jate the room, lined their intended victims against the wall and ordered them to march enterly	built in the Assambly chamber, the Board of Regents, the just
A Challenge of Facts. To this Dr. Compton countered	with the decorum befitting the se- casion, submuly inhibe an as yes undetermined number of	"The only way to learn whather	a memorandum to all South American Foreign Offices demanding the	Anti-Keenig Resolution. The resolution asking Mr. Keenig's	Police Department, who jumped out of a rear window, unacticed by the	into the rear room. Dr. Lewis happened to be near the door and	of the Court of Appeals and o notables, numbering in all at 560, will been seen at a Mar-
with a direct challenge of facts. Last year, under Dr. Compton's inferencia, a number of ministific	muge, steins, houkers, schouners or buckets of beer of the alroholis	to tast it by having men drink R. After all, that is the test the whole	right to be considered a party to any negotiations between Feru and Colembia arising from the scout	resignation was introduced by Samuel A. Berger, an attorney and member of the sinh. It read as fail	store to telephone the alarm. The men, who were taken com-	in was the work of a moment for him to slip out and jump from the window. In two or three minutes	TELMAN T
expeditions set out to study the econds ray is eighty-one different	fore the committee for report. The members of the committee	country will apply to the beer if we pees this law and permit the manu- facture and sale of 3.3 per cent	conflict, claiming propriatary rights in the Amazon basis and soping	Whereas the Republican ergani-	pletely by surprise by the sudday appearance of four policemen with drawn guns, had taken 5555 and	more, Patroimen Edward Noian. Morris Glickhause, Joseph Torris	DDBVATELY
bar, over the Alps, on Mount Me- Kinley in Alarka, in Islands of the	would observe the effect of these potations upon the drinkars, 22	"Those who support the beer bill	mand or make any sacrifice acces- sary to protect her soutrality in	in so far as its jeadership by Sam- uel S. Koenig, county chairman.	some jewsity from their victims when they were caught. They gave	the warning by radio, were at the scene.	PRIVATELY
Pacific and at stations near the north and south magnetic poles.	meanor of the jury of tastars it would be chvious that 3.2 per cent	calling. They should have no objec- tion to such a test as this. It is	event of hostilities between Peru	is concerned, has lost the confi- dence of the members of this er-	Manhatian, as follows: John Ru- bins, 22 years old, 150 Cherry	Except for a slight limp enume by his jump from the second-story window. Dr. Learnin way	CEREMONY
Mount McEnley during their stoffer.	beer is non-intoxicating. Should the jurymen sing, dance, tall stories, weep, fall from their chairs or seek	the desire of the American people that the Volstand act he amended so as to permit the manufacture	can countries not mentioned in the dispatch, at least two are gravely	this district and of the other Re- publican veters of the County of	Street; John Siciliano, 28, of 202 East 112th Street; Thomas Ro- maine, 18, of 401 East N	One young woman fainted during the excitement but she was re-	SHOW SUMMAR
The opervalions of all these dif-	to embrare members of the com-	and sale of non-integication has	concerned over their preaimity to	Hew Tork.	Street and John Other of 431 Free	vived.	Interi

MILLIKAN RETORTS Hotly to compton In cosmic ray clash

Debate of Rival Theorists Brings Drama to Session of Nation's Scientists.

THEIR DATA AT VARIANCE

New Findings of His Ex-Pupil Lead to Thrust by Millikan at 'Less Cautious' Work.

Energy spectrum CR are observed over a remarkable range of energies



Cosmic ray spectrum (credit: HAP / A. Chantelauze)

Maximum energy detected to date: 50 J (~ K.E. of Roger Federer 2nd serve)

Total energy density ~ 1 eV cm^{-3}

... somewhat LARGER than that of starlight, the CMB, or the Galactic B-field

Table 1.5	Energy	Densities	in	the	Local	ISM
-----------	--------	-----------	----	-----	-------	-----

Component	$u(eV cm^{-3})$	Note
Cosmic microwave background $(T_{CMB} = 2.725 \text{ K})$	0.265	a
Far-infrared radiation from dust	0.31	b
Starlight $(h\nu < 13.6 \mathrm{eV})$	0.54	c
Thermal kinetic energy $(3/2)nkT$	0.49	d
Turbulent kinetic energy $(1/2)\rho v^2$	0.22	e
Magnetic energy $B^2/8\pi$	0.89	f
Cosmic rays	1.39	g
a Fixsen & Mather (2002).		
b Chapter 12.		
c Chapter 12		

 $d \text{ For } nT = 3800 \text{ cm}^{-3} \text{ K}$ (see §17.7).

 $e \text{ For } n_{\rm H} = 30 \text{ cm}^{-3}, v = 1 \text{ km s}^{-1}, \text{ or } \langle n_{\rm H} \rangle = 1 \text{ cm}^{-3}, \langle v^2 \rangle^{1/2} = 5.5 \text{ km s}^{-1}.$

 $f\,$ For median $B_{\rm tot}\approx 6.0\,\mu{\rm G}$ (Heiles & Crutcher 2005).

g For cosmic ray spectrum X3 in Fig. 13.5.

Draine, 2011

Interaction with the interstellar gas

 High energy (E > 280 MeV) cosmic ray protons create γ-rays via

> $CR + p \rightarrow CR + p + \pi^{0}$ $\pi^{0} \rightarrow \gamma + \gamma$

- Lower energy cosmic rays ionize and heat the ISM $CR + H \rightarrow CR + H^+ + e$ $CR + H_2 \rightarrow CR + H_2^+ + e$
- Secondary electrons can cause additional ionization and heating, and can excite UV emissions from H and H₂ (important in dense clouds where starlight is absent)

Interaction with the interstellar gas

 Key parameter: the Cosmic Ray Ionization Rate (CRIR) There are three quantities that are often used but not always distinguished

ζ_p(H): Primary ionization rate per H atom
 ζ_t(H): *Total* ionization rate per H atom
 (i.e. including further ionizations by secondary e)
 ζ_t(H₂):Total ionization rate per H₂ molecule

The exact relationship depends on the ionization state of the gas (because the secondary electrons can lose energy through elastic collisions with cold electrons, but the rough ratios are (Glassgold and Langer 1974)

 $ζ_t(H) = 1.5 ζ_p(H)$ $ζ_t(H_2) = 2.3 ζ_p(H)$

What CRIR is expected?

• Key obstacle in relating observations of cosmic-rays to the interstellar CRIR:

The ionization rate is dominated by lower energy CR than any that can be detected

At the location of the Earth, "solar modulation" (due to Sun's B-field and the solar wind) reduces the flux of CR below ~ 1 GeV

What CRIR is expected?

Cummings et al. 2016

In situ measurements by Voyager I show a large reduction in solar modulation effects beyond 122 AU



What CRIR is expected?

Cummings et al. 2016

Cummings et al. (2016) estimate the implied CRIR as



However, there are three critical caveats

- The ionization cross-sections peak at CR energies below what can be observed (even with Voyager I) → still need to extrapolate the CR energy spectrum
- It's not entirely clear whether solar modulation effects are still significant
- 3) In any case, the results apply only to the local ISM

Cloud types in the ISM (Snow and McCall, 2006, ARAA)



Cloud types in the ISM (Snow and McCall, 2006, ARAA)

Table 1 Classification of Interstellar Cloud Types Translucent Diffuse Atomic **Diffuse Molecular** Dense Molecular Defining Characteristic $f^{n}_{C^{+}} < 0.5 f^{n}_{CO} < 0.9$ $f^{n}_{H_{2}} < 0.1$ $f^{n}_{H_{2}} > 0.1 f^{n}_{C^{+}} > 0.5$ $f^{n}_{CO} > 0.9$ 0 ~ 0.2 $\sim 1 - 2$ $\sim 5 - 10$ A_V (min.) Typ. $n_{\rm H}$ (cm⁻³) $>10^{4}$ 10 - 100100-500 500-5000? Typ. T (K) 30 - 10030-100 15-50? 10-50 Vis (UV?) IR abs Observational UV/Vis UV/Vis IR abs IR abs Techniques H I 21-cm mm abs mm abs/em mm em

Cloud types in the ISM (Snow and McCall, 2006, ARAA)

Table 1 Classification of Interstellar Cloud Types **Diffuse** Atomic Diffuse Molecular Translucent **Dense Molecular Defining Characteristic** $f^{n}_{H_{2}} < 0.1$ $f^{n}_{H_{2}} > 0.1 f^{n}_{C^{+}} > 0.5$ $f^{n}_{C^{+}} < 0.5 f^{n}_{CO} < 0.9$ $f^{n}_{CO} > 0.9$ 0 $\sim 5 - 10$ A_V (min.) $\sim 1 - 2$ ~ 0.2 Typ. $n_{\rm H}$ (cm⁻³) $>10^{4}$ 10 - 100100-500 500-5000? Typ. T (K) 30 - 10015-50? 10 - 5030 - 100Vis (UV?) IR abs Observational UV/Vis UV/Vis IR abs IR abs Techniques HI21-cm mm abs/em mm abs mm em

Observations of H¹³CO⁺ Avg. $\zeta_p(H) = 1.1 \times 10^{-17} \text{ s}^{-1}$ (van der Tak & van Dishoeck 2000)

Temperature of starless cores (Keto & Caselli 2008) → similar results Measuring the cosmic-ray ionization rate in *diffuse* molecular clouds with H₃⁺ In diffuse *molecular* clouds, H₃⁺ production <u>follows ionization of H₂</u>



McCall et al. (2003): CRIR along sight-line to ζ Per $\zeta_p(H) = 5 \times 10^{-16} \text{ s}^{-1}$ Indriolo & McCall (2012): Best-estimate of average CRIR $\zeta_p(H) = 1.5 \times 10^{-16} \text{ s}^{-1}$

1980

Observation of the Infrared Spectrum of ${ m H}_3^+$

Takeshi Oka Phys. Rev. Lett. **45**, 531 – Published 18 August 1980

|--|

ABSTRACT

The infrared ν_2 band of H_3^+ has been observed. A direct infrared absorption method combining a liquid-nitrogen-cooled multiple-reflection discharge cell and a difference-frequency laser system has been used for the detection. Fifteen absorption lines have been measured in the region of 2950-2450 cm⁻¹ and assigned. This is the first spectroscopic detection of this fundamental molecular ion in any spectral range.

1996

Letter

Detection of H_{3}^{+} in interstellar space

T. R. Geballe & T. Oka

Nature **384**, 334–335 (28 November 1996) doi:10.1038/384334a0 Download Citation Received: 14 August 1996 Accepted: 22 October 1996 Published: 28 November 1996

Abstract

THE H_{3}^{+} ion is widely believed to play an important role in interstellar chemistry, by initiating the chains of reactions that lead to the production of many of the complex molecular species observed in the interstellar medium^{1–5}. The presence of H_{3}^{+} in the interstellar medium was first suggested⁶ in 1961, and its infrared spectrum was measured⁷ in the laboratory in 1980. But attempts^{8–11} to detect it in interstellar space have hitherto proved unsuccessful. Here we report the detection of H_{3}^{+} absorption in the spectra of two molecular clouds. Although the present results do not permit an accurate determination of the H_{3}^{+} abundances, these ions appear nevertheless to be present in sufficient quantities to drive much of the chemistry in molecular clouds. It should soon be possible to obtain more accurate measurements, and thus better quantify the role of ion–neutral reactions in the chemical evolution of molecular clouds.



Letter

An enhanced cosmic-ray flux towards ζ Persei inferred from a laboratory study of the H₃⁺-e⁻ recombination rate

B. J. McCall [™], A. J. Huneycutt, R. J. Saykally, T. R. Geballe, N. Djuric, G. H. Dunn, J. Semaniak, O. Novotny, A. Al-Khalili, A. Ehlerding, F. Hellberg, S. Kalhori, A. Neau, R. Thomas, F. Österdahl & M. Larsson

Nature **422**, 500–502 (03 April 2003) doi:10.1038/nature01498 Download Citation Received: 19 November 2002 Accepted: 17 February 2003 Published: 03 April 2003 Measuring the cosmic-ray ionization rate in *diffuse* molecular clouds with H₃⁺ In diffuse *molecular* clouds, H₃⁺ production <u>follows ionization of H₂</u>



McCall et al. (2003): CRIR along sight-line to ζ Per $\zeta_p(H) = 5 \times 10^{-16} \text{ s}^{-1}$ Indriolo & McCall (2012): Best-estimate of average CRIR $\zeta_p(H) = 1.5 \times 10^{-16} \text{ s}^{-1}$

The CRIR in diffuse *molecular* clouds revisited with detailed models

Variation with cloud N(H₂):

Black points: clouds with direct measurements of H_2 and density estimates from C_2

Blue points: clouds <u>without</u> direct measurements of H_2 but with density estimates from C_2

Marginally significant evidence for a decline in $\zeta_p(H)$ with N(H₂) or A_V(tot)

Effect of shielding?

Consistent with the difference between the CRIRs derived for diffuse and dense molecular clouds (factor ~ 20)



Neufeld and Wolfire 2017, ApJ

Cloud types in the ISM (Snow and McCall, 2006, ARAA)

Table 1 Classification of Interstellar Cloud Types

	Diffuse Atomic	Diffuse Molecular	Translucent	Dense Molecular
Defining Characteristic	$f^{n}_{H_{2}} < 0.1$	$f^{n}{}_{H_2} > 0.1 \ f^{n}{}_{C^+} > 0.5$	$f^{n}{}_{C^{+}} < 0.5 \ f^{n}{}_{CO} < 0.9$	$f^n_{CO} > 0.9$
A _V (min.)	0	~0.2	~1-2	~5–10
Typ. n _H (cm ⁻³)	10–100	100–500	500-5000?	>10 ⁴
Тур. Т (К)	30–100	30–100	15-50?	10–50
Observational	UV/Vis	UV/Vis IR abs	Vis (UV?) IR abs	IR abs
Techniques	H I 21-cm	mm abs	mm abs/em	mm em



Cloud types in the ISM (Snow and McCall, 2006, ARAA)

Table 1 Classification of Interstellar Cloud Types

	Diffuse Atomic	Diffuse Molecular	Translucent	Dense Molecular
Defining Characteristic	$f^{n}_{H_{2}} < 0.1$	$f^{n}{}_{H_2} > 0.1 \ f^{n}{}_{C^+} > 0.5$	$f^{n}{}_{C^{+}} < 0.5 \ f^{n}{}_{CO} < 0.9$	$f^n_{CO} > 0.9$
A _V (min.)	0	~0.2	~1-2	~5-10
Тур. n _H (ст ⁻³)	10–100	100–500	500-5000?	>10 ⁴
Тур. Т (К)	30–100	30–100	15-50?	10–50
Observational	UV/Vis	UV/Vis IR abs	Vis (UV?) IR abs	IR abs
Techniques	H I 21-cm	mm abs	mm abs/em	mm em



Thermochemistry for different elements

	Element	lonization Potential	Endothermic	Driver		
		(eV)	$X + H_2 \rightarrow XH + H$	$X^+ + H_2 \rightarrow XH^+ + H$	$X + H_{3^{+}} \rightarrow XH^{+} + H_{2}$	
	С	11.260	11000	4640 🗹		Warm gas
	Ν	14.534	15000	230	10000	?
Important	0	13.618	940 🗹		\checkmark	Warm gas or cosmic rays
ormation	F	17.423			10000	None needed
bathway	Ne	21.564	No reaction	Exothermic, but primary channel is to Ne + H + H ⁺	27000	
	Si	8.152	17000	15000		Warm gas
Gerin et al. ARAA 2016	Р	10.487	19000	13000		Warm gas
	S	10.360	10000	10000 🗹		Warm gas
	Cl	12.968	450	\checkmark		UV with hv > 12.97 eV
	Ar	15.760	No reaction		6400	Cosmic rays

Exothermic reaction of element in its main ionization state Endothermic reaction of element in its main ionization state



Exothermic reaction of element <u>not</u> in main ionization state



Endothermic reaction of element <u>not</u> in main ionization state Measuring the cosmic-ray ionization rate with OH⁺ and H_2O^+ O is not ionized by UV radiation longward of the Lyman limit, so OH⁺ and H_2O^+ formation must be initiated by cosmic ray ionization



Measuring the cosmic-ray ionization rate with OH⁺ and H_2O^+ OH⁺ and H_2O^+ are observable with Herschel/HIFI



Neufeld, Goicoechea, Sonnentrucker et al. 2010, A&A

Full dataset provides ~ 100 column density measurements (Indriolo et al. 2015, ApJ)

PRISMAS Herschel Key Program

PRobing the ISM with Absorption line Studies

High spectral-resolution observations of diffuse clouds lying along the sight-line to bright THz continuum sources

A very "clean" experiment providing robust estimates of molecular column densities

H column densities available from 21 cm observations with VLA (Winkel et al. 2017)



Credit: NASA/SSC

Detailed diffuse cloud models: OH⁺ and H₂O⁺ abundances

Current model (Neufeld & Wolfire 2017) refines earlier treatment by Hollenbach et al. (2012): constant density slab models in steady-state

Extensive parameter study carried out for 2880 combinations of relevant parameters. Note: results scale with χ_{UV} / n_H and $\zeta_p(H)$ / n_H

UV radiation field to Draine (1978) e	relative estimate	Parameter	Number of values	Values
	~	$\chi_{\rm UV}$ $\zeta_{\rm p}({\rm H})/10^{-16}s^{-1}$	10 9	0.05, 0.1, 0.2, 0.3, 0.5, 1.0, 2.0, 3.0, 5.0, 10.0 0.006, 0.02, 0.06, 0.2, 0.6, 2.0, 6.0, 20, 60
Total extinction through cloud	>	$A_{ m V}({ m tot})/{ m mag}$	16	0.0003, 0.001, 0.003, 0.01, 0.03, 0.1, 0.2, 0.3, 0.5, 0.8, 1.0, 1.5, 2.0, 3.0, 5.0, 8.0
Metallicity relative to ISM in solar neighborhood		$Z/Z_{\rm std}$ $n_{\rm H}$	2 1	1.0, 2.0 $50 \mathrm{cm^{-3}}$

In gas phase: O/H = 3.9×10^{-4} , C/H = 1.6×10^{-4} , Ar/H = 3.2×10^{-6}

Detailed diffuse cloud models: OH⁺ and H₂O⁺ abundances

Predicted column density ratios (Neufeld and Wolfire 2017), with observed values from Indriolo et al. (2015)

Key predicted behaviors

Predicted N(OH⁺)/N(H₂O⁺) decreases with A_V(tot) Larger A_V(tot) means more H₂, which means more H₂O⁺

Predicted N(OH⁺)/N(H) increases with ζ_p(H) Reaction pathway initiated by H ionization



Additional constraints from ArH⁺

Argonium (ArH⁺) has been widely observed in the diffuse ISM through its 617 GHz J = 1 - 0 absorption line (identified by Barlow et al. 2013 only several years after it was first detected)

It is rapidly destroyed by H_2 in the reaction ArH⁺ + $H_2 \rightarrow$ Ar + H_3^+

and attains its maximum abundance when $f_{H2} = 2n(H_2) / [2n(H_2) + n(H)] \sim 10^{-4}$ A molecular tracer of *almost purely atomic* gas Additional constraints from ArH⁺ Argon production is initiated by direct ionization of Ar by cosmic-rays



Observed ArH⁺, OH⁺ and H₂O⁺ abundances imply that ~ 20 – 50% of the cold neutral ISM is in a separate population of material with $f_{H2} = 10^{-5}$ to 10^{-2} and A_V(tot) < 0.02 mag (Neufeld & Wolfire, 2016)

The CRIR in diffuse atomic clouds

Average value obtained from 32 determinations of the CRIR

< $\zeta_p(H)$ > = (2.2 ± 0.3) x 10⁻¹⁶ s⁻¹ standard error on the mean (statistical)

Intrinsic variation in the CRIR $\sigma(\log_{10} [\zeta_p(H)/n_{50}]) = 0.23$ (a factor 1.7)

Cloud types in the ISM (Snow and McCall, 2006, ARAA)

Table 1 Classification of Interstellar Cloud Types

	Diffuse Atomic	Diffuse Molecular	Translucent	Dense Molecular
Defining Characteristic	$f^{n}_{H_{2}} < 0.1$	$f^{n}{}_{H_2} > 0.1 \ f^{n}{}_{C^+} > 0.5$	$f^{n}{}_{C^{+}} < 0.5 \ f^{n}{}_{CO} < 0.9$	$f^n_{CO} > 0.9$
A _V (min.)	0	~0.2	~1-2	~5–10
Typ. $n_{\rm H}$ (cm ⁻³)	10–100	100–500	500-5000?	>10 ⁴
Тур. Т (К)	30–100	30–100	15-50?	10–50
Observational	UV/Vis	UV/Vis IR abs	Vis (UV?) IR abs	IR abs
Techniques	H I 21-cm	mm abs	mm abs/em	mm em



From H₃⁺ $\zeta_p(H) = 2.3 \pm 0.6 \times 10^{-16} \text{ s}^{-1}$ (with marginal evidence for decline with A_V(tot))

From HCO⁺ (van der Tak & van Dishoeck 2000) $\zeta_p(H) = 1.1 \times 10^{-17} \, s^{-1}$

The CRIR in diffuse atomic clouds

Important caveat: uncertainty estimates include only statistical errors and not uncertainties in reaction rates

Key reactions:

H⁺ + PAH → PAH⁺ + H	(1
H⁺ + O → O⁺ + H	(2
$O^+ + H \rightarrow H^+ + O$	(3
$O^+ + H_2 \rightarrow OH^+ + H$	(4
$OH^+ + H_2 \rightarrow H_2O^+ + H$	(5
OH⁺ + e → O + H	(6

CRIR estimates are

- (1) an increasing function of k_5 and k_6
- (2) inversely proportional to k₄
- (3) proportional to k_1 and k_3/k_2

In LTE, k_3/k_2 is fixed by detailed balance, but in diffuse clouds OI is subthermally populated

If rate k_2 for O(³P₂) is abnormally low (suggested by Spirko et al. 2003), then CRIR must increase to match data.

Lines of very high principal quantum number *n* (~ 250 to 900) are detectable from diffuse atomic clouds (rather than HII regions)

Best example: stacked absorption spectra obtained toward Cas A by Oonk et al. (2017) using the Westerbork Synthesis Radio Telescope (WSRT)

Cn α lines are shifted relative to Hn α lines by -149 km s⁻⁻¹ (due to smaller reduced mass)



Oonk et al. (2017)

Rydberg states

0.1 (n/1000)² mm



Lines of very high principal quantum number *n* (~ 250 to 900) are detectable from diffuse atomic clouds (rather than HII regions)

Best example: stacked absorption spectra obtained toward Cas A by Oonk et al. (2017) using the Westerbork Synthesis Radio Telescope (WSRT)

Cn α lines are shifted relative to Hn α lines by -149 km s⁻⁻¹ (due to smaller reduced mass)



Oonk et al. (2017)

Dependence of line strength on n
 probe of density and temperature

Ratio of HRRL to CRRL strengths

 probe of CRIR in diffuse atomic gas
 CRRL come from C⁺, produced by photoionization
 HRRL come from H⁺, produced by CR ionization

(First discussed by Sorochenko and Smirnov 1987)





Best-fit parameters $T = 87 \pm 2 \text{ K}$ $n_{e} = 0.041 \pm 0.001 \text{ cm}^{-3}$

*1 sigma statistical uncertainties



Ratio of HRRL/CRRL places constraints on CRIR

From this, Oonk et al 2017 got a lower limit of 1.1 x 10^{-18} s⁻¹ on $\zeta_p(H)$, by assuming that H⁺ is destroyed solely by radiative recombination

However, two additional processes are much more important in removing H⁺

H⁺ + PAH → H + PAH⁺ H⁺ + O → H + O⁺ (followed by O⁺ + H₂ → OH⁺ + H)

 $\zeta_p(H) = 8 \times 10^{-17} \text{ s}^{-1}$ (Neufeld et al. 2018, ApJ, submitted) UV field = 6 x mean IS field $n_H = 220 \text{ cm}^{-3}$



Cloud types in the ISM (Snow and McCall, 2006, ARAA)

Table 1 Classification of Interstellar Cloud Types

	Diffuse Atomic	Diffuse Molecular	Translucent	Dense Molecular
Defining Characteristic	$f^{n}_{H_{2}} < 0.1$	$f^{n}{}_{H_2} > 0.1 \ f^{n}{}_{C^+} > 0.5$	$f^{n}{}_{C^{+}} < 0.5 \ f^{n}{}_{CO} < 0.9$	$f^n_{CO} > 0.9$
A _V (min.)	0	~0.2	~1-2	~5–10
Typ. $n_{\rm H}$ (cm ⁻³)	10–100	100–500	500-5000?	>10 ⁴
Тур. Т (К)	30–100	30–100	15-50?	10–50
Observational	UV/Vis	UV/Vis IR abs	Vis (UV?) IR abs	IR abs
Techniques	H I 21-cm	mm abs	mm abs/em	mm em



Summary and conclusions

- Remarkable concordance between three independent methods for estimating the CRIR in diffuse atomic and molecular clouds: all yield $\zeta_p(H) = 0.8 2.3 \times 10^{-16} \text{ s}^{-1}$
- CRIR in diffuse clouds is a factor of 20 to 30 larger than that estimated for dense clouds

Suggests that CR are excluded from dense clouds NB: Observations of diffuse molecular clouds do show (marginal) evidence for CRIR decreasing with N_H

 CRIR in diffuse clouds is a factor of 20 to 30 larger than estimates based on latest Voyager data

> Possible explanations: LISM is atypical, solar modulation is still important at current location of Voyager I, X-ray ionization is important in ISM, and/or extrapolation of CR spectrum is wrong